

Université du Québec

**Institut national de la recherche scientifique- Énergie, Matériaux-
Télécommunications**

**A programmable passive amplifier based on temporal self-imaging
(Talbot) effect and application**

by

Jinwoo Jeon

A Thesis presented for the Master degree of Telecommunication

Jury of evaluation

Internal examiner (President of the jury)	:	JINYANG LIANG INRS-EMT, Canada
External examiner	:	PABLO BIANUCCI Concordia University, Canada
Research supervisor	:	JOSÉ AZAÑA INRS-EMT, Canada

© Jinwoo Jeon, April 2018

ABSTRACT

The temporal Talbot effect, also referred to as temporal self-imaging effects (TSI) is observed when a periodic pulse train propagates through a first-order dispersive medium. Under specific dispersion conditions, either an exact or a repetition-rate multiplied self-image of the input signal is reproduced at the output. Moreover, the TSI possesses an interesting self-restoration capability, which proves effective even when acting over an aperiodic train of pulses. Besides its compelling interest as a physical phenomenon, the TSI has additionally been put into practice in several areas.

This work targets application of TSI in two different fronts, namely for signal intensity amplification and for clock recovery in telecommunication systems, with a focus on optical-domain waveform processing. On the one hand, signal intensity amplification is an essential process in plentiful of applications, including for initiating physical processes, diagnostics, sensing, communications and measurement, just to name a few. On the other hand, clock recovery (CR) from data coded signals is a fundamental functionality to establish the needed synchronization in high-speed telecommunication links and signal-processing platforms, including systems based on optical signals. In these two applications, the notion of programmability is of fundamental importance. To begin with, it is obvious that for any amplification system, the capability of tuning the amplifier gain is crucial for a practical, real-world use of the amplifier. In regards to the CR problem, it should be noted that it is often desired to have access to the capability of recovering a clock signal (e.g., periodic pulse train), synchronized with the incoming data packet, with a pulse rate either identical to the symbol rate of the data signal (base-rate CR, or BR-CR) or at a divided rate with respect to the input data (sub-harmonic CR, or SH-CR). SH-CR is particularly interesting in the context of time-division multiplexing systems. The capability of tuning the clock rate with respect to the input data provides an additional important versatility in the telecommunication or signal-processing platform at hand.

An advanced new feature of TSI, referred to as inverse temporal self-imaging (I-TSI), has been recently reported that enables to obtain a self-image of an incoming periodic temporal waveform (e.g., optical pulse train) but with a divided repetition rate. This is achieved through a lossless process that incorporates a suitably designed temporal phase-modulation stage before the dispersive medium. I-TSI has been demonstrated for passive amplification of repetitive optical waveforms, as induced by a lossless repetition-rate division of the incoming waveform, as well as to recover the sub-harmonic clock signal from pulsed telecommunication data signals.

Unfortunately, in previous designs for passive waveform amplification and sub-harmonic clock recovery based on I-TSI, a different gain factor or a different clock rate-division factor required the use of a different amount of dispersion, a significant and unpractical modification in the amplifier setup. The possibility of achieving a reconfigurable gain factor or rate division factor in these systems constitutes the central scope of this work. In this context, the main contribution reported in this thesis resides in the derivation of a non-trivial generalization of the I-TSI equations (i.e., designing equations for the phase modulation and dispersive stages), which allow us to obtain a relatively wide range of different gain factors, or the associated rate-division factors, using a fixed dispersion, by suitably programming the temporal phase modulation step. Such a reconfigurability can be achieved by electronic means using an electro-optic phase modulator for implementation of the temporal phase modulation step. Experimental results are reported to validate the newly proposed design for passive Talbot amplification of repetitive optical waveforms in which the gain factor can be electrically reconfigurable. An all-fiber design is also demonstrated for a programmable base/sub-harmonic optical clock recovery circuit from pulsed (return-to-zero, RZ) telecommunication data signals, in which the divided clock rate can be electrically reconfigurable as well.

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my supervisor, Prof. Jose Azana for his guidance and constant support in helping me to conduct and complete this work. I really appreciate him for encouraging my research and allowing me to grow up as a researcher.

Beside my supervisor, I would like to acknowledge with much appreciation my co-workers Dr. Reza Maram and Prof. James Van Howe. They continually and persuasively helped me in all the time of research and writing this thesis.

I am indebted to all past, present and honouree members of the UOP Lab: Dr. Mohamed Seghilani, Dr. Xiao-Zhou Li, Dr. María del Rosario Fernández Ruiz, Dr. Hamed Pishvai Bazargani, Luis Romero Cortés, Jeonghyun Huh, Saikrishna Reddy, and Saket Kaushal. Thank you so much for your help but most importantly for your friendship.

Many thanks to all the people I have come to know in INRS-EMT especially Achref Methenni, whose friendship and companionship I will always enjoy. I owe my sincere appreciation to my family and relatives who have supported and encouraged me over the years. I especially want to deeply thank Junghee Hwang for her inspiration and continuous encouragement during my studies. Finally, I want to extend my profound appreciation to my beloved parents and brother for their love, affection, and invaluable support during my life.

Jinwoo Jeon

TABLE OF CONTENTS

ABSTRACT.....	I
ACKNOWLEDGEMENT.....	III
LIST OF FIGURES.....	VII
RESUME	XI
1.1 Contexte et motivations.....	XIII
1.2 Problèmes et Objectifs de Recherche	XVII
1.3 Organisation de la thèse.....	XXIII
1.4 Effet temporel de Talbot.....	XXIV
1.4.1 Dispersion chromatique temporelle	XXV
1.4.2 Auto-imagerie (ou effet Talbot) temporelle induite par la dispersion.....	XXIX
1.4.3 Auto-imagerie temporelle inverse conventionnelle (I-TSI).....	XXXV
1.4.4 Conception généralisée pour I-TSI	XXXVIII
1.4.5 Considérations sur les implémentations pratiques de I-TSI	XL
CHAPTER ONE: INTRODUCTION	1
1.1 Background and Motivations.....	1
1.2 Research Problem and Objectives	5
1.3 Thesis Organization	10
1.4 Temporal Talbot Effect.....	11
1.4.1 Temporal chromatic dispersion.....	12
1.4.2 Dispersion-induced temporal self-imaging (TSI) or temporal Talbot effect.....	16
1.4.3 Conventional inverse temporal self-imaging (I-TSI).....	22
1.4.4 Generalized design for I-TSI.....	24
1.4.5 Considerations on practical implementation of I-TSI.....	26
1.5 References and Links.....	28
CHAPTER TWO: PROGRAMMABLE PASSIVE TALBOT OPTICAL WAVEFORM AMPLIFIER.....	35
2.1 Abstract.....	35

2.2 Introduction.....	35
2.3 Principle of operation.....	36
2.4 Experimental results	40
2.5 Conclusion.....	45
2.6 References and links.....	46

CHAPTER THREE: PRGORAMMABLE SUB-HARMONIC OPTICAL CLOCK RECOVERY.....49

3.1 Abstract.....	49
3.2 Introduction.....	49
3.3 Principle of operation.....	51
3.4 Experimental results.	56
3.5 Conclusion.....	59
3.6 References and links.....	60

CHAPTER FOUR: CONCLUSION AND PERSPECTIVES.....61

4.1 Conclusions.....	61
4.2 Perspectives.....	62

PUBLICATIONS.....64

LIST OF FIGURES

Fig. 1.1-Schematic diagram of the space-time duality (a) Spatial equivalent of the self-imaging. (b) Temporal equivalent of the self-imaging. The representations show the case of the integer self-imaging effect. Adapted from Ref. [65].....	2
Fig. 1.2- Method for phase preconditioning pulse trains for dispersion-induced I-TSI effect. PM: phase modulator. DM: dispersive medium (a) Talbot passive amplification (b) SH clock recovery from an on-off-key (OOK) data modulated pulse train.....	3
Fig. 1.3- Programmable method for phase preconditioning pulse trains for dispersion-induced I-TSI effect. PM: phase modulator. DM: dispersive medium.....	5
Fig. 1.4-Active amplification setup: Erbium Doped Fiber Amplifier setup schematic.....	6
Fig. 1.5-Coherent pulse amplification with the aid of an optical cavity.....	7
Fig. 1.6(a) Standard temporal Talbot effect, illustrating the evolution of a repetitive input pulse train through propagation along a first-order dispersive medium (b) Talbot passive waveform amplification concept (PM: phase modulator, DM: dispersive medium).....	8
Fig. 1.7- Pulse broadening effect by linear propagation through a first-order dispersive medium.....	13
Fig. 1.8-Temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium.....	17
Fig. 1.9-Joint time-frequency analysis of the temporal Talbot effect. t : time, f : frequency.....	20
Fig. 1.10-Temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium and the residual temporal phase variations of the resulting temporal pulse trains (represented by the dashed blue lines).....	21
Fig. 1.11-The standard temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium. Talbot carpet when for different repetition periods: (a) $T'=6T$; (b) $T''=3T$; (c) $T'''=2T$	22
Fig. 1.12-The original design for the conventional Talbot amplifier. Coherent addition of repetitive pulse waveforms is achieved by tailoring the temporal phase of the input waveform train and subsequent propagation through a dispersive medium such that the individual waveform intensity (energy) is amplified by an amount the repetition rate is reduced. Adapted from Ref. [12].....	24
Fig. 1.13-Programmable method for phase preconditioning pulse trains for dispersion-induced I-TSI effect. PM: phase modulator. DM: dispersive medium.....	26
Fig. 2.1-Concept for programmable Talbot amplification: (a) Talbot carpet when the input repetition period $T'=3T$ (b) Talbot carpet when the input repetition period $T''=2T$. Pulse trains with	

repetition period T , at $z=z_T'/3$ and $z=z_T''/2$, result in different amplification factors using the same amount of dispersive delay (purple shading). The dashed blue lines represent the phase profiles of each of the temporal pulse trains in the carpet.....	37
Fig. 2.2-Method for phase preconditioning pulse trains for dispersion-induced temporal Talbot amplification. PM: phase modulator. DM: dispersive medium.....	39
Fig. 2.3-Experimental setup. MLL: mode-locked laser, BPF: band-pass filter, OA: optical amplifier, OD: optical delay line, PC: polarization controller, PM: phase modulator, LC-FBG: linearly chirped fiber Bragg grating, CLK: radio frequency clock source, AWG: arbitrary waveform generator, RF Amp: radio frequency (RF) amplifier.....	41
Fig. 2.4-Experimental results of the demonstrated programmable passive amplifier. (a) Prescribed temporal phase profile. The dashed black lines: Ideal temporal phase profile. The solid green lines: Actual phase profile drive generated from the AWG. (b) Measured optical spectra of the optical pulse trains after temporal phase modulation. Dashed, blue, double-arrow shows a 0.154-nm (19.2-GHz) span.....	42
Fig. 2.5-Experimental results of the demonstrated programmable passive amplifier. Temporal traces of the input and amplified output pulses (Input: dashed gray, Output: solid red), measured using a 500-GHz sampling oscilloscope.	43
Fig. 2.6-Superimposed single temporal pulse waveforms measured at the system output for the different amplification factors achieved in the experiment.....	45
Fig. 3.1-Operation principle illustration of the proposed programmable BR/SH CR concept. PM: temporal phase modulator. GVD: group-velocity dispersion.....	52
Fig. 3.2-Numerical simulation results of the programmable BR/SH CR. (a) Ideal temporal phase modulation profiles derived from Eq. 3.2(a) and 3.2(b). (b) Temporal waveforms (data input on top). (c) Eye diagrams.....	54
Fig. 3.3-Sub-harmonic clock signal's amplitude-variations as a function of the input temporal pulse width for different bit rate-division factors (m). Estimates from the experimentally recovered waveforms are plotted in red	55
Fig. 3.4-Experimental setup for the programmable BR/SHCR through dispersion induced temporal self-imaging. MLL: actively mode-locked laser, MZM: Mach-Zehnder modulator, OD: optical delay line, PC: polarization controller, PM: phase modulator, LC-FBG: linearly chirped fiber-Bragg grating, AWG: arbitrary waveform generator, OSO: optical sampling oscilloscope, OSA: optical spectrum analyzer.....	56

Fig. 3.5-(a) Theoretically prescribed (dashed black) and experimentally implemented (solid green) temporal phase modulation profiles (b) Measured optical spectra at the output of the programmable BR/SH CR circuit, corresponding to the cases $m = 1, 2, 5,$ and 10 . Dashed, black, double-arrow shows a 0.08-nm (11.1-GHz) span57

Fig. 3.6-Experimental proof-of-concept results of the proposed programmable BR/SH CR concept. (a) Temporal waveforms and eye-diagrams of the input data signal and recovered optical clock when the system is programmed to achieve BR/SH CR ($m = 1$), and SHCR (for $m = 2, 5,$ and 10). Temporal waveform measurements are averaged by 4 times. (b) Corresponding RF spectra of the signals shown in (a)..... 59

RESUME

L'effet Talbot temporel, également appelé effets d'auto-imagerie temporelle (TSI, pour 'Temporal self-imaging' en anglais), est observé lorsqu'un train d'impulsions périodiques se propage à travers un milieu dispersif de premier ordre. Dans des conditions de dispersion spécifiques, l'image du signal d'entrée est reproduite en sortie avec un taux de répétition identique ou multiplié. En outre, le TSI possède une capacité d'auto-restauration intéressante qui s'avère efficace même lorsqu'elle agit sur un train d'impulsions apériodiques. Outre son intérêt incontestable en tant que phénomène physique, le TSI a également été utilisé pour des applications pratiques dans plusieurs domaines.

Ce travail vise l'application de la TSI sur deux fronts différents, à savoir l'amplification de l'intensité du signal et la récupération de l'horloge dans les systèmes de télécommunication, en mettant l'accent sur le traitement des formes d'onde dans le domaine optique. D'une part, l'amplification de l'intensité du signal est un processus essentiel dans de nombreuses applications, y compris pour initier des processus physiques, les diagnostics, les capteurs, les communications et la métrologie, pour n'en citer que quelques-uns. D'autre part, la récupération d'horloge (CR, pour 'clock recovery') à partir de signaux de données est une fonctionnalité fondamentale pour établir la synchronisation nécessaire dans les liaisons de télécommunication à haute vitesse et les plates-formes de traitement du signal, y compris les systèmes basés sur des signaux optiques. Dans ces deux applications, la notion de programmabilité est d'une importance fondamentale.

Pour commencer, il est évident que pour tout système d'amplification, la capacité de réglage du gain de l'amplificateur est cruciale pour une utilisation pratique et réelle de l'amplificateur. En ce qui concerne le problème CR, il convient de noter que l'on souhaite souvent avoir accès à la capacité de récupérer un signal d'horloge (par exemple un train d'impulsions périodiques) synchronisé avec le paquet de données entrant, avec une fréquence d'impulsion identique au taux de symboles du signal de données (récupération de l'horloge à débit de base, ou BR-CR, pour 'base rate CR') ou à un taux divisé par rapport aux données d'entrée (récupération de l'horloge sous-harmonique, ou SH-CR pour 'sub-harmonic CR'). L'application SH-CR est particulièrement intéressante dans le contexte des systèmes de multiplexage temporel. La possibilité de régler la fréquence d'horloge par rapport aux données d'entrée fournit une polyvalence supplémentaire et importante dans la plate-forme de télécommunication ou de traitement du signal.

Une nouvelle fonctionnalité avancée du TSI, appelée auto-imagerie temporelle inverse (I-TSI, pour inverse-TSI), a récemment été rapportée. Elle permet d'obtenir l'auto-image d'une forme d'onde temporelle périodique entrante (par exemple, un train d'impulsions optiques) mais avec une division du taux de répétition. Ceci est réalisé grâce à un processus sans perte qui incorpore une étape de modulation de phase temporelle adéquate avant le milieu dispersif. L'I-TSI a été démontré pour l'amplification passive de formes d'onde optiques répétitives, induite par une division sans perte de la fréquence de répétition de la forme d'onde entrante, ainsi que pour récupérer le signal d'horloge sous-harmonique des signaux de télécommunication à impulsions.

1.1 Contexte et motivation

L'effet d'auto-imagerie temporelle (TSI, pour 'Temporal self-imaging' en anglais) a attiré l'attention et a suscité l'engouement des chercheurs au cours de la dernière décennie. Le TSI, également appelé effet Talbot temporel, est l'équivalent temporel du phénomène bien connu d'auto-imagerie spatiale [1-3]. Les systèmes d'imagerie temporelle et les phénomènes d'auto-imagerie temporelle (Talbot) sont des exemples d'application de la théorie de la dualité espace-temps. La figure 1.1 illustre schématiquement la dualité espace-temps entre les effets d'auto-imagerie spatiale et temporelle [4]. Le TSI se produit lorsqu'un train périodique d'impulsions optiques se propage à travers un milieu dispersif dans une approximation du premier ordre; un tel milieu dispersif est caractérisé par une réponse d'amplitude passe-tout linéaire et une variation de phase quadratique avec la fréquence. Une quantité appropriée de la dispersion du premier ordre, donnée par la condition dite d'auto-imagerie [1, 2], conduit soit à une reproduction exacte du train d'impulsions initial (effet TSI entier, représenté sur la Fig. 1.1) ou à une multiplication du taux de répétition d'impulsion par un nombre entier (effet TSI fractionnaire). Ces caractéristiques intéressantes de l'effet TSI permettent de répondre aux demandes récentes des applications émergentes, en particulier pour les télécommunications optiques. En fait, les propriétés physiques intrinsèques du phénomène de TSI ont été utilisées pour de nombreuses applications importantes.

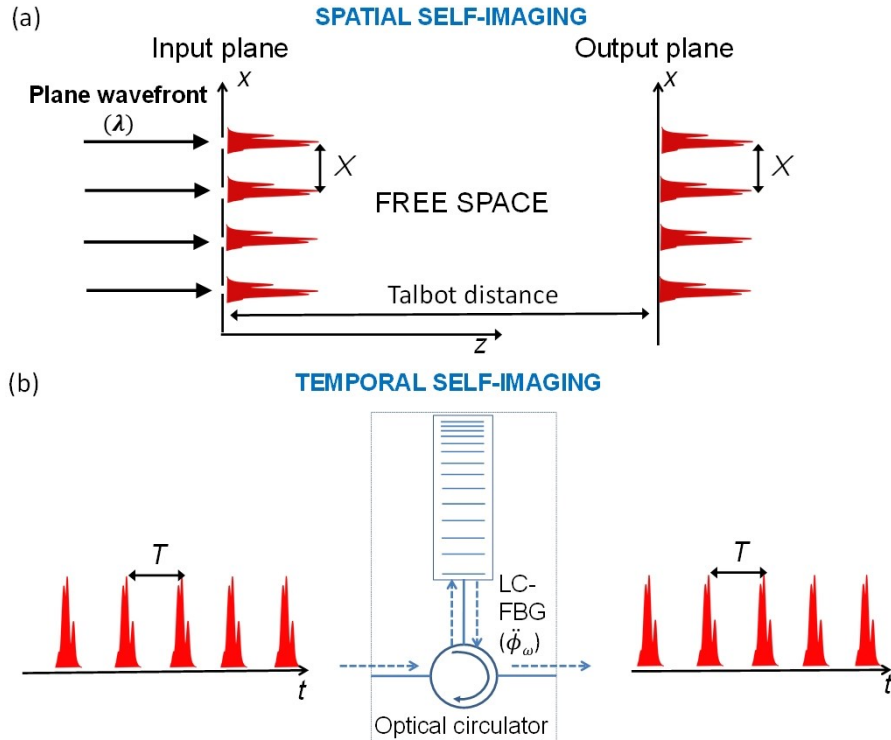


Figure. 1.1- Diagramme schématique de la dualité espace-temps (a) Équivalent spatial de l'auto-imagerie. (b) Équivalent temporel de l'auto-imagerie. Les représentations montrent le cas de l'effet d'auto-imagerie en nombre entier. Adapté de la Réf. [4].

- Le TSI fractionnaire a fait l'objet d'études approfondies pour la multiplication sans perte du taux de répétition d'un train d'impulsions périodiques [5-10]. Le plus souvent, des fibres optiques monomode (SMF, pour 'single mode fibers' en anglais) [11-13] ou des réseaux de Bragg LC-FBG [2, 14-15] ont été utilisés comme milieux dispersifs pour des mises en œuvre pratiques.
- Ce phénomène a été théoriquement étudié pour mesurer avec précision le coefficient de dispersion de premier ordre d'un milieu dispersif [2].
- Il a été démontré que la capacité de tampon inhérente au TSI génère une sortie périodique, même à partir d'un train d'impulsions apériodiques à l'entrée. Cette propriété a été utilisée pour récupérer, sans perte, le signal d'horloge à taux de base (BR) à partir de flux de données apériodiques, par exemple avec un format de retour à zéro (RZ-OOK) [16-17]. Encore une fois, des SMF et des LC-FBG ont été utilisés pour la mise en œuvre pratique des milieux dispersifs requis [2, 11-15].

- Plus récemment, une nouvelle caractéristique du TSI, à savoir, l'auto-imagerie temporelle inverse (I-TSI), a été démontrée permettant de diviser, sans perte, le taux de répétition de la forme périodique entrante par un facteur désiré [18-19]. L'I-TSI implique l'utilisation d'une étape de modulation adéquate de la phase temporelle avant le milieu dispersif du premier ordre. L'I-TSI (pour 'inverse-TSI') constitue le principe de base d'une technique d'amplification passive et sans bruit des signaux optiques répétitifs en utilisant une conception tout-fibre et sans utiliser de gain actif [18]. La figure 1.2 (a) fournit une illustration du schéma I-TSI utilisé pour l'amplification passive de formes d'onde répétitives [18].
- L'amplificateur passif basé sur l'I-TSI a la capacité d'atténuer le bruit temporel présent sur les signaux d'entrée, tels que la réduction des fluctuations d'intensité d'impulsion-à-impulsion et de la gigue temporelle [20]. En tant qu'extension de cette propriété intéressante, l'I-TSI a été utilisé pour la récupération d'horloge sous-harmonique (SH-CR, pour 'sub-harmonic clock recovery') à partir de signaux de données de télécommunication à impulsions, c'est-à-dire avec une fréquence d'horloge divisée par un facteur désiré par rapport au débit symbole des données entrantes [3]. La figure 1.2 (b) fournit une illustration de l'application SH-CR du schéma I-TSI [3].

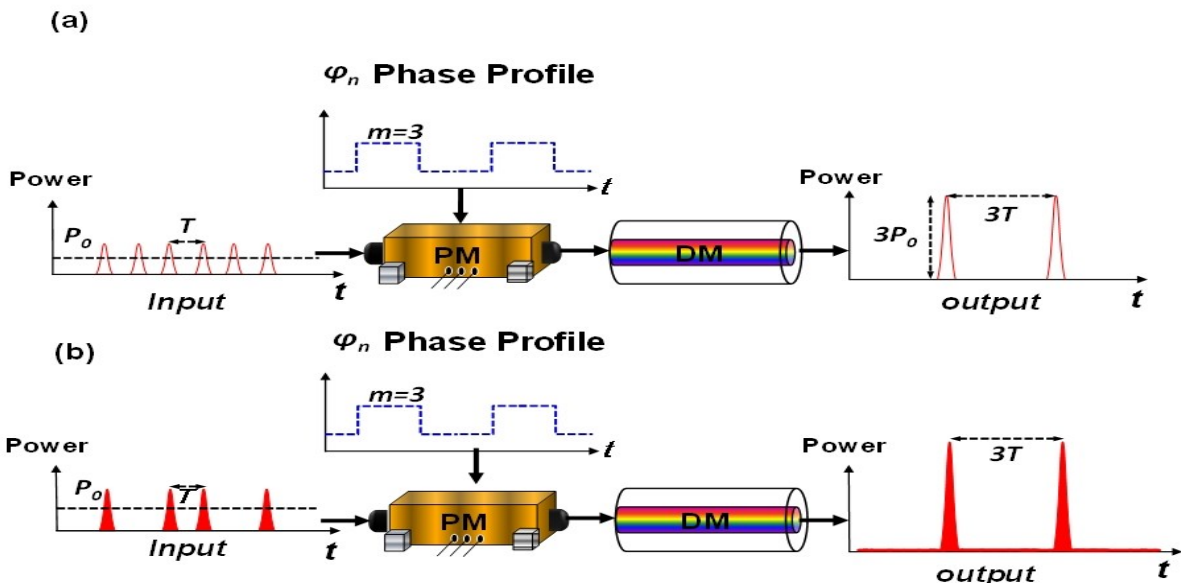


Figure 1.2 - Méthode de pré-conditionnement de la phase des trains d'impulsions pour l'effet I-TSI induit par la dispersion. PM: modulateur de phase. DM: milieu dispersif (a) Amplification passive de Talbot (b) Récupération du signal d'horloge SH à partir d'un train d'impulsions modulées par des données de type on-off-key (OOK).

L'une des principales applications du TSI induite par la dispersion est la multiplication du taux de répétition des impulsions optiques [10]. Il a été prouvé que le facteur de multiplication du taux de répétition peut être programmé en incorporant une étape de modulation de phase temporelle avant le milieu dispersif. Une variété de facteurs de multiplication peut être atteinte en programmant convenablement le signal de modulation de phase dans le système [10]. La reconfigurabilité électronique du processus de multiplication est possible grâce à la modulation électro-optique de la phase, dans laquelle le train d'impulsions optiques entrant est modulé par un signal électronique, par exemple généré par un générateur de formes d'ondes arbitraires [10]. En revanche, les conceptions conventionnelles pour l'amplification de Talbot [18] et les circuits SH-CR associés [3] ne permettent pas de programmation électronique, c'est-à-dire d'ajuster les spécifications clés du système, à savoir le gain de l'amplificateur ou le facteur de division du taux de répétition pour le circuit SH-CR de Talbot.

Ce travail vise la conception et la démonstration d'un amplificateur de Talbot passif et programmable, et d'un circuit programmable de récupération de l'horloge sous-harmonique (SH-CR). Ces deux blocs exploitent une conception inverse du TSI, appelée I-TSI [3, 18]. Comme mentionné ci-dessus, ceci nécessite l'utilisation d'une étape de modulation de phase temporelle avant le milieu dispersif pour induire un processus de division de taux de répétition sans perte. Néanmoins, dans les conceptions publiées précédemment [3,18], il est nécessaire de changer la dispersion pour changer le facteur de division du taux de répétition, c'est-à-dire changer le facteur de gain pour l'amplificateur de Talbot ou le facteur de division de la fréquence d'horloge dans la récupération d'horloge sous-harmonique (SH-CR). Par conséquent, l'approche de conception I-TSI conventionnelle ne permet pas d'accorder (et donc de programmer) le facteur de gain ou le facteur de division de la fréquence d'horloge, sans modifier physiquement l'élément dispersif, une modification substantielle et peu pratique. Évidemment, comme pour tout appareil amplificateur, la capacité de réglage du facteur de gain est critique pour les applications pratiques de l'amplificateur. En outre, la récupération du signal d'horloge à partir d'un signal de données optique avec un débit programmable fournit une flexibilité supplémentaire et importante dans la plate-forme de télécommunication ou de traitement du signal.

Dans ce travail, je rapporte une généralisation non triviale des équations de l'effet I-TSI (équations de conception pour la modulation de phase requise), ce qui permet d'obtenir une gamme d'accord relativement large du facteur de division du taux de répétition, ou le facteur de gain d'impulsion équivalent) en utilisant une dispersion fixe, en programmant de manière appropriée la modulation de phase temporelle induite sur le train d'impulsions. La

programmabilité électronique du gain dans l'amplificateur de Talbot, ou la fréquence de l'horloge récupérée dans le circuit SH-CR, est alors possible et démontrée ici en utilisant un étage de modulation de phase électro-optique, comme illustré sur la Fig.1.3 pour le cas d'amplificateur Talbot.

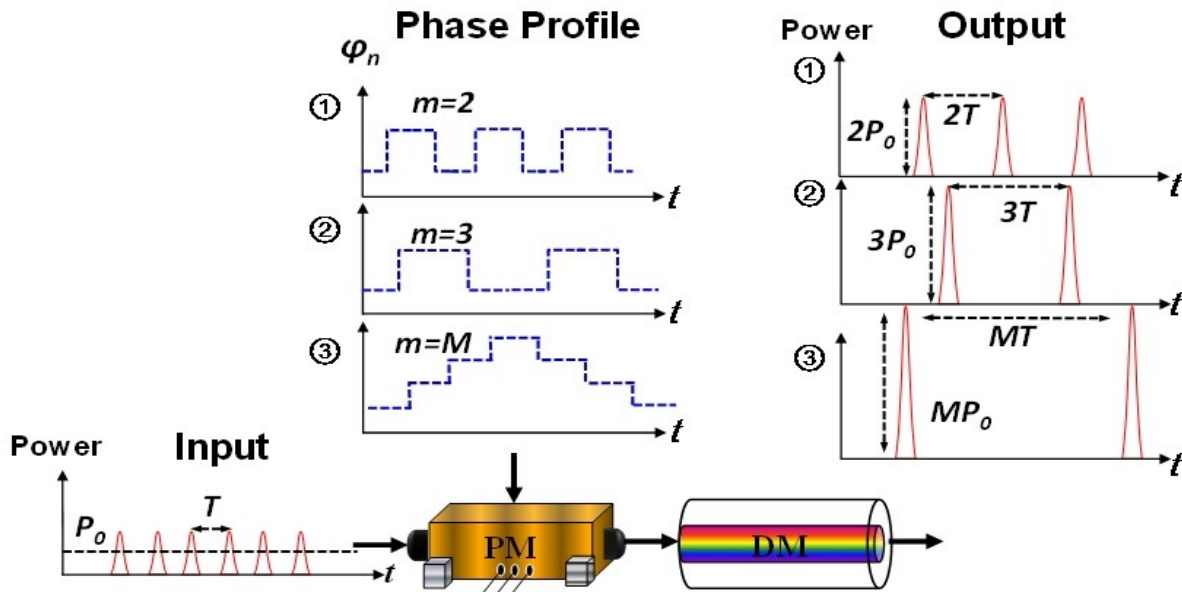


Figure 1.3 - Méthode pour pré-conditionnement de la phase des trains d'impulsions pour le I-TSI programmable induit par dispersion. PM: modulateur de phase. DM: milieu dispersif.

1.2 Problèmes de recherche et objectifs

L'amplification du signal est essentielle dans les systèmes de télécommunication pour la compensation des pertes de puissance accumulées, causées par une variété de processus liés au signal et la propagation. En outre, il existe diverses applications qui nécessitent des impulsions optiques de haute intensité, y compris la microscopie non linéaire [21], l'informatique optique, et le traitement des matériaux [22]. Différents types d'amplificateurs optiques ont été démontrés dans le passé, tel que l'amplificateur à fibre optique dopé à l'erbium (EDFA, pour 'erbium-doped optical fiber amplifier') [23], l'amplificateur optique à semi-conducteur (SOA, pour 'semiconductor optical amplifier') [24], l'amplificateur Raman à fibre (FRA, pour 'fiber Raman amplifier') [25], etc. Tous ces amplificateurs reposent sur des mécanismes de *gain actifs*, où le signal est amplifié directement en multipliant les porteuses de signaux par un processus alimenté par une source externe [26-33]. Il est indiscutable que l'EDFA est particulièrement pertinent dans le contexte des systèmes de communication optique longue distance. Cependant, un EDFA nécessite d'utiliser une source externe pour alimenter le processus de

gain actif afin d'amplifier un signal. Comparée à la solution EDFA, le SOA est avantageux en termes d'efficacité énergétique [34]. Cependant, ce type d'amplificateurs souffre toujours de défauts critiques, tels qu'un bruit élevé, un faible gain, une sensibilité à la polarisation, et une non-linéarité élevée avec un temps transitoire rapide. Quant à l'amplificateur Raman, le principe de FRA est basé sur le gain de Raman, qui résulte de l'effet de diffusion Raman stimulée. En raison de l'effet Raman, le FRA présente certaines limitations importantes, par exemple liées à des exigences de puissance de pompage élevées et à la nécessité d'un contrôle sophistiqué du gain.

La figure 1.4 montre un exemple simple d'un processus d'amplification active classique, illustré ici par un EDFA. Le circuit est composé du milieu à gain actif et d'une source laser de pompage, une exigence clé dans tout processus d'amplification active. De plus, l'emploi de l'amplification active contribue au bruit d'amplitude et au bruit de phase du signal, par exemple, à travers le bruit de l'émission spontanée amplifiée (ASE, pour 'amplified spontaneous emission') ou la gigue temporelle [36-37], et peut induire d'autres distorsions de signal dues à la bande passante limitée de l'amplificateur. Comme le processus de gain actif ajoute son propre bruit dans le signal d'entrée en plus d'amplifier intrinsèquement le bruit préexistant dans ce signal, le rapport signal sur bruit (SNR, pour signal-to-noise ratio) à la sortie diminue inévitablement [18]. Cela dégrade le facteur du bruit, communément utilisé comme un indicateur de qualité des amplificateurs actifs, et qui est défini comme le rapport entre le SNR du signal d'entrée et le SNR du signal de sortie [38]. Bien que des amplificateurs sensibles à la phase aient été montrés capables de réaliser une amplification à faible bruit (avec des facteurs de bruit obtenus expérimentalement aussi faibles que 1 dB [33]), ceux-ci impliquent l'utilisation de processus non linéaires complexes et inefficaces. Généralement, l'amplification des signaux faibles par les amplificateurs classiques généralement noie le signal dans le bruit et le rend totalement indétectable [18].

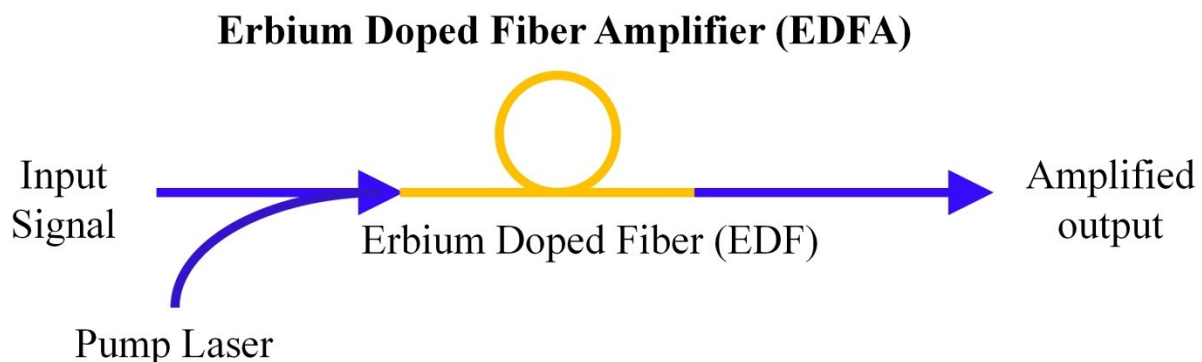


Figure 1.4- Configuration de l'amplification active : amplificateur à fibre dopée à l'Erbium.

Il est à noter également que dans les applications nécessitant des impulsions optiques à puissance de crête élevée [21-22, 39], l'amplification active traditionnelle est extrêmement inefficace. Afin de générer des impulsions optiques à puissance de crête élevée, de nombreuses impulsions dans le train d'ondes sont volontairement jetées 'prélèvement d'impulsions', avant l'amplification [40] ou pendant le processus d'amplification (amplification régénérative) [41] pour concentrer l'énergie de la source externe dans un nombre réduit d'impulsions de sortie.

Afin de surmonter les inconvénients décrits ci-dessus, des amplificateurs passifs ont été démontrés dans le passé pour amplifier *des formes d'onde répétitives* (par exemple des impulsions optiques) par addition d'onde cohérente sans utiliser un milieu de gain actif [42-43]. Cependant, l'addition cohérente de nombreuses formes d'ondes identiques est extrêmement difficile. La figure 1.5 montre le principe de fonctionnement du processus d'amplification passive classique. Dans ce système, un train de forme d'onde répétitif est stocké et ajouté de façon cohérente à lui-même dans une cavité de haute finesse, ce qui conduit à l'accumulation (et donc l'amplification) de formes d'onde en sortie. Ainsi, ces procédés requièrent un contrôle très précis de la phase de l'enveloppe du signal d'entrée et de sa porteuse optique, y compris la stabilisation de la phase enveloppe-porteuse, afin de stabiliser la forme d'onde d'entrée dans la cavité de sorte que chaque impulsion soit ajoutée constructivement dans la sortie amplifiée. Ces exigences sont souvent peu pratiques en dehors du laboratoire. Spécifiquement, les petits déphasages de chaque impulsion tendent vers une interférence destructive à la sortie.

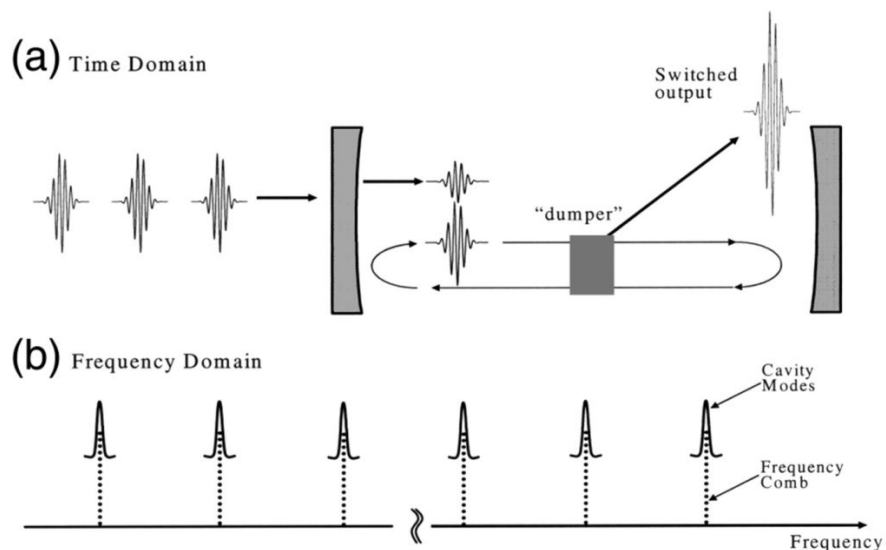


Figure 1.5 - Amplification d'impulsions cohérente à l'aide d'une cavité optique.

Récemment, notre groupe a démontré une nouvelle technique d'amplification passive simple, et entièrement basée sur une conception tout-fibre, pour des formes d'onde répétitives sans

utiliser de processus de gain actifs [18]. La figure 1.6 illustre le concept de la technique d'amplification passive de Talbot, qui exploite les temps de renouvellement de cohérence intrinsèque des trains d'ondes périodiques fournis par l'élargissement dispersif passif, connu sous le nom d'auto-imagerie temporelle ou l'effet Talbot temporel (voir Fig. 1.6, en haut). L'amplification passive est obtenue en redistribuant efficacement et en ajoutant de façon cohérente l'énergie d'entrée d'un signal de forme d'onde répétitive en un nombre réduit de formes d'onde, ce qui fait que chaque forme d'onde de sortie est une réplique amplifiée de l'entrée. Pour la mettre en œuvre, nous exploitons l'effet d'auto-imagerie temporelle inverse (I-TSI) dans lequel l'image temporelle amplifiée finale est récupérée à partir d'une auto-image précédente multipliée [18]. L'amplificateur de Talbot passif fournit la réplique amplifiée désirée d'un train d'impulsions optiques d'entrée sans déformer les caractéristiques individuelles d'impulsion en appliquant une simple combinaison de modulation de phase temporelle et de propagation à travers un milieu dispersif. Contrairement aux méthodes traditionnelles d'addition cohérente d'impulsions [42], la technique de Talbot met en œuvre un processus similaire sans cavité résonnante et les contraintes de synchronisation et de stabilisation rigoureuses qui lui sont associées. La seule condition est que la forme d'onde d'entrée soit répétitive et conserve sa cohérence sur toute la durée déterminée par la période de répétition de sortie. Comme la technique d'amplification Talbot passive est basée sur le processus fondamental de superposition linéaire des ondes, elle peut être appliquée à tous les systèmes utilisant des signaux répétitifs, y compris des régions du spectre électromagnétique ou d'autres plateformes ondulatoires où des processus de gain actifs pour l'amplification des formes d'ondes sont limité ou n'existent pas.

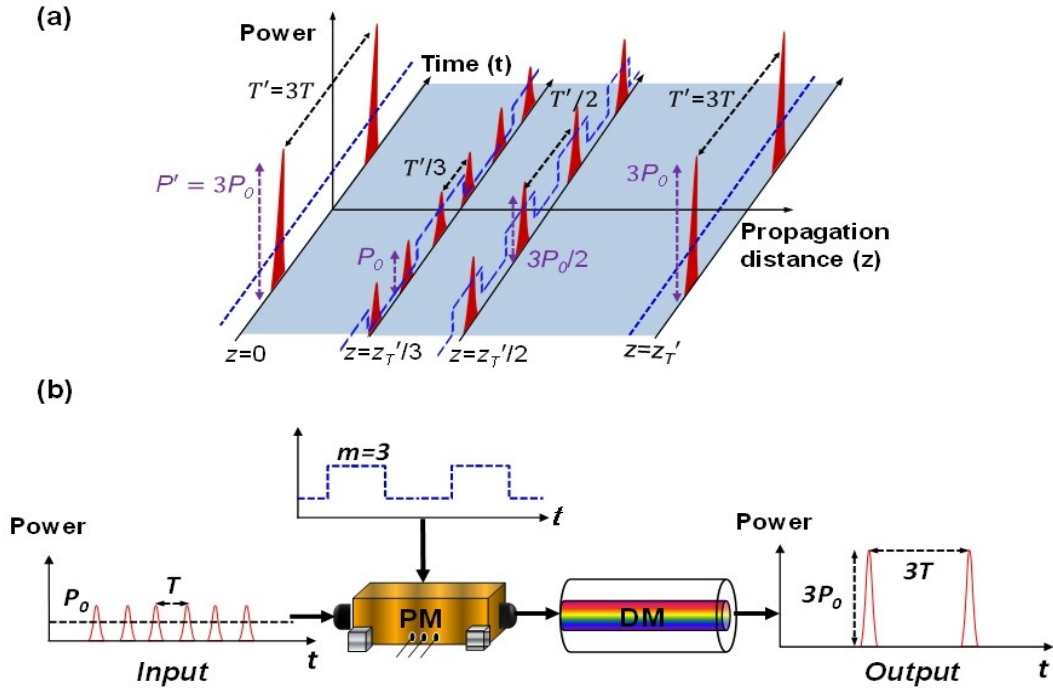


Figure 1.6- (a) Effet de Talbot temporel standard, illustrant l'évolution d'un train d'impulsions périodique à l'entrée par propagation le long d'un milieu dispersif de premier ordre. (b) Concept d'amplification passive de Talbot des formes d'ondes (PM: modulateur de phase, DM: milieu dispersif).

Malgré ces divers avantages de l'amplification passive de Talbot mentionnée ci-dessus, il existe une limitation principale en ce qui concerne le contrôle du facteur de gain, qui est une capacité clé de tout amplificateur. Comme discuté, le travail précédent a utilisé une longueur de milieu dispersif fixe pour un facteur de gain donné, ce qui nécessite l'utilisation de différents milieux dispersifs pour modifier le facteur de gain. Ceci représente une modification importante - éventuellement peu pratique - dans la configuration expérimentale, limitant la flexibilité de cette conception pour atteindre une valeur de gain souhaitée. Par conséquent, dans ce travail, je propose et démontre expérimentalement une version généralisée de l'amplification passive de Talbot dans laquelle le facteur de gain peut être reconfigurable électriquement. De même que la conception précédente [18], le montage expérimental de l'amplificateur est composé d'un modulateur de phase électro-optique suivi d'un milieu optique dispersif. En généralisant les équations pour la modulation de phase et la dispersion requises pour induire l'effet I-TSI désiré, nous sommes capables d'obtenir une gamme de divers facteurs de gain en utilisant une dispersion fixe, c'est-à-dire sans changer le milieu dispersif. Nos expériences de preuve de faisabilité ont démontré avec succès l'amplification en-fibre d'impulsions optiques picosecondes

avec des facteurs de gain accordables de 2 à 30, en utilisant un réseau de Bragg sur fibre à pas linéairement variable (LC-FBG) comme milieu dispersif.

En plus de ce travail, la conception nouvellement proposée basée sur I-TSI peut être employée pour un circuit programmable de récupération d'horloge de base ou sous-harmonique (BR/SH-CR pour 'base rate or sub-harmonic clock recovery'). L'extraction de l'horloge cadencée à partir des signaux optiques reçus, connue sous le nom d'extraction de synchronisation optique, est également une fonctionnalité de grande importance dans le contexte des opérations synchrones dans un système de télécommunication optique à grande vitesse. En particulier, la récupération d'horloge de base (BR/SH-CR) est indispensable pour de nombreuses fonctions clés telles que la régénération 3R [44] et les techniques générales de traitement du signal [45]. De plus, la récupération d'horloge sous-harmonique (SHCR) (réduction du taux de répétition par rapport au débit de base des données d'origine) est une technique intéressante qui permet de récupérer une horloge optique pour la synchronisation à un débit inférieur. Généralement, l'horloge SH peut être manipulée avec une électronique de fréquence inférieure, une caractéristique généralement intéressante et particulièrement importante pour effectuer des opérations de démultiplexage et de traitement ultérieur du signal dans des systèmes optiques multiplexés par répartition dans le temps (OTDM, pour 'optical time-division multiplexing') [46-49]. Il a déjà été rapporté que les signaux d'horloge à taux de base et sous-harmonique peuvent être récupérés sans perte à partir d'un signal de données optique RZ-OOK (Return-to-Zero On-Off-Keying) en exploitant l'effet TSI [1-2]. En effet, le TSI est un principe physique unique qui permet de générer les deux signaux d'horloge dans une seule plateforme.

En particulier, Pudo et al., ont montré la capacité de tampon inhérente de l'effet TSI pour générer une sortie périodique, même à partir d'un train d'impulsions apériodiques à l'entrée, et cela a été utilisé pour récupérer l'horloge à taux de base pour un signal de données optiques RZ-OOK en utilisant des fibres monomodes (SMFs) ou des réseaux de Bragg sur fibres à pas linéairement variable (LC-FBG) en tant que milieu dispersif [16-17]. Dans un travail connexe, Reza et al., ont démontré que l'effet I-TSI peut également être exploité pour générer une sortie périodique (avec un taux de répétition divisé, c'est-à-dire sous-harmonique) à partir d'un train d'impulsions apériodique à l'entrée, propriété qui pourrait être utilisée pour récupérer le signal d'horloge sous-harmonique (SHCR) à partir d'un signal de données RZ-OOK [3]. Néanmoins, ce système SHC utilise une longueur fixe de milieu dispersif pour un facteur de division de débit donné, il n'est donc pas simple d'ajuster le facteur de division sans changer l'élément dispersif - une reconfiguration significative du système. Une nouvelle conception pour la récupération programmable d'horloge à taux de base ou sous-harmonique (BR/SH) a été étudiée

numériquement et démontrée expérimentalement dans ce travail. Dans cette nouvelle conception le facteur de division de fréquence d'horloge peut être reconfiguré électriquement. De manière similaire à l'amplificateur programmable, la configuration de récupération d'horloge proposée est composée d'un modulateur de phase électro-optique suivi d'un milieu dispersif à fibres optiques. Comme mentionné ci-dessus, grâce à la généralisation introduite ici sur les équations de l'effet I-TSI, le facteur de division de fréquence est facilement accordable en programmant la fonction de modulation de phase. Je rapporte ici une analyse numérique de la technique SHCR reconfigurable proposée, et une démonstration expérimentale de preuve de faisabilité sur un signal de données RZ-OOK à 11,1 Gbit/s.

1.3 Organisation de ce mémoire

Le chapitre 1 -en cours- introduit l'effet Talbot temporel; l'analyse théorique de l'effet et ses propriétés fondamentales sont expliquées. La mise en œuvre des conceptions proposées pour l'amplificateur de Talbot programmable et la récupération d'horloge programmable BR/SH sont introduites. Les systèmes proposés exploitent l'effet d'auto-imagerie temporelle (aussi appelé Talbot) inverse (I-TSI), pour obtenir une division sans perte du taux de répétition d'un train périodique de forme d'onde arbitraire (p. ex, impulsion). Le système proposé utilise une combinaison de modulation de phase temporelle (par exemple, mise en œuvre par modulation de phase électro-optique) et de dispersion dans une fibre optique pour traiter le train de forme d'onde périodique entrant. Nous présentons ici le principe de notre généralisation proposée des équations I-TSI, qui permet la réalisation d'un processus d'amplification de Talbot programmable et d'un processus de récupération d'horloge BR/SH programmable. Cette nouvelle conception I-STI généralisée nous permet d'obtenir différents facteurs de division de fréquence avec un milieu dispersif fixe en programmant de manière appropriée l'étape de modulation de phase temporelle.

Dans le chapitre 2, je présente la dérivation détaillée des équations I-STI généralisées. Pour valider le principe proposé, ce chapitre montre les résultats d'un processus d'amplification passive programmable basé sur l'effet I-TSI généralisé, où les intensités des impulsions de sortie peuvent être reconfigurées électriquement sans changer le milieu dispersif.

Le chapitre 3 porte sur l'application de la théorie I-STI généralisée pour construire un circuit de récupération d'horloge BR/SH programmable, où les signaux d'horloge sous-harmonique et de base sont extraits avec succès d'un signal de données $2^7 - 1$ PRBS 11.1Gbit/s sans changer le milieu dispersif, d'une manière électriquement reconfigurable.

Le chapitre 4 résume le travail présenté dans ce mémoire et suggère des perspectives futures potentielles.

1.4 L'effet Talbot temporel

L'effet Talbot, également appelé auto-imagerie ou imagerie sans lentille, est un effet de diffraction en champ proche qui a été observé avec la lumière [43, 50-53], voir Fig. 1.1, le graphique du haut. Lorsqu'une onde plane se propage à travers un réseau ou une autre structure périodique, le front d'onde qui en résulte se propage de telle sorte qu'il reproduit la structure à des multiples d'une certaine distance, connue sous le nom de longueur de Talbot. L'Effet Talbot a été découvert par son éponyme, Henry Fox Talbot, au milieu du dix-huitième siècle. Il a travaillé pour produire des images qui resteraient fixées sur un film. Ces expériences ont abouti à l'expansion de sa renommée, comme il est maintenant connu comme l'un des inventeurs de la photographie [54]. Pendant ses études, il a observé l'effet remarquable qui porte maintenant son nom. Quand il a examiné un réseau de diffraction grossièrement dirigé avec une lentille grossissante simple, Talbot a remarqué que l'image du réseau réapparaîtrait alors qu'il déplaçait le réseau hors foyer. Quand le réseau est éclairé par une lumière blanche, cette dernière se diviserait en différentes couleurs, et la lumière monochromatique provoquerait la mise au point de l'image à des multiples d'une distance particulière. Talbot a publié les résultats de certaines de ses expériences sur le sujet en 1836, mais n'a pas poursuivi l'étude du phénomène, puisqu'il investissait son temps et son argent dans la photographie. Un demi-siècle plus tard, l'effet Talbot a été redécouvert par Lord Rayleigh en 1881. Rayleigh l'a expliqué comme une conséquence naturelle de la diffraction de Fresnel, et a montré que la longueur de Talbot z_T est donnée par

$$z_T = \frac{a^2}{\lambda} \quad (1.1)$$

où a est la période du réseau et λ est la longueur d'onde de la lumière incidente. Rayleigh a également mentionné que l'effet Talbot pourrait avoir une application pratique pour reproduire des réseaux en exposant le film à l'une des images reproduites derrière le réseau d'origine [50]. Chronologiquement, l'effet Talbot basé sur la théorie classique de la diffraction a été redécouvert par Winkelmann [51], Weisel [52] et Wolfke [53] au début du siècle dernier, en essayant de comprendre la formation d'images en microscopie. Au milieu des années 1950, Cowley et Moodie ont étudié en profondeur les propriétés du champ de diffraction de Fresnel

derrière des objets périodiques, où ils ont trouvé que la structure du réseau se répliquait à des multiples d'une certaine distance longitudinale, z_T .

La dualité bien connue entre la diffraction paraxiale des faisceaux optiques dans le domaine spatial et la distorsion temporelle des impulsions à bande étroite dans un milieu dispersif a été largement étudiée pour introduire et établir des analogues temporels des systèmes spatiaux [55]. En raison des analogies mathématiques entre la diffraction spatiale et la dispersion temporelle, l'équivalent temporel de l'effet spatial de Talbot, appelé effet Talbot temporel, a été décrit pour la première fois par T. Jansson et J. Jansson en 1981 [56]. L'effet Talbot temporel se produit lorsqu'un signal optique temporellement périodique se propage à travers un milieu dispersif dans des conditions de dispersion de premier ordre [56], voir l'exemple d'illustration de la Fig. 1.1(b). Jansson et Jansson ont trouvé les distances dans une fibre auxquelles un signal répétitif d'entrée est exactement reproduit. Depuis lors, l'effet Talbot temporel a suscité un intérêt remarquable [1-2, 11, 57]. Une motivation centrale vient du fait que l'effet Talbot temporel peut être utilisé pour multiplier le taux de répétition d'un train périodique d'impulsions sans déformer les caractéristiques d'impulsion individuelles (telles que le profil temporel et la durée) par simple propagation linéaire de ce train d'impulsions à travers un milieu dispersif de premier ordre (p. ex, un tronçon de fibre optique conventionnelle) [11-13]. La multiplication du taux de répétition est produite fondamentalement sans aucune perte de l'énergie d'entrée (à l'exception de possibles pertes passives pratiques dans le milieu dispersif).

1.4.1 Dispersion chromatique temporelle

Avant d'entrer dans les détails de l'effet Talbot temporel, il convient de décrire le terme 'milieu dispersif', qui est la composante clé de la réalisation de cet effet. Lorsqu'une onde électromagnétique interagit avec les électrons liés d'un diélectrique, la réponse du milieu dépend en général de la fréquence optique (radiale) ω . Cette propriété, appelée dispersion chromatique, se manifeste par la dépendance en fréquence de l'indice de réfraction [58]. Sur le plan fondamental, l'origine de la dispersion chromatique est liée aux fréquences de résonance caractéristiques auxquelles le milieu absorbe le rayonnement électromagnétique par l'oscillation des électrons liés. L'effet est par exemple observé lorsque la lumière se propage à travers un guide d'onde optique composé de matériaux diélectriques (par exemple, une fibre optique). Dans ce cas particulier, la dispersion chromatique est une conséquence de la dépendance en fréquence des indices de réfraction des diélectriques impliqués (dispersion du matériau) ainsi que de la dépendance en fréquence des propriétés de propagation du faisceau lumineux, par

exemple l'angle de propagation (dispersion du guide d'onde) [58], de sorte que l'effet global est ensuite caractérisé par la dépendance en fréquence d'un indice de réfraction efficace, désigné ici par $n(\omega)$ simplicité et pour assurer la généralité de la formulation présentée.

La dispersion des fibres joue un rôle essentiel dans la propagation des impulsions optiques courtes [58] car différentes composantes spectrales associées à l'impulsion se déplacent à différentes vitesses, données par $c/n(\omega)$, où c est la vitesse de la lumière dans l'espace libre et $n(\omega)$ représente la dépendance de l'indice de réfraction n à la fréquence. Même lorsque les effets non linéaires ne sont pas importants, l'élargissement des impulsions induit par la dispersion peut être préjudiciable aux systèmes de communication optique [58], voir figure 1.7.

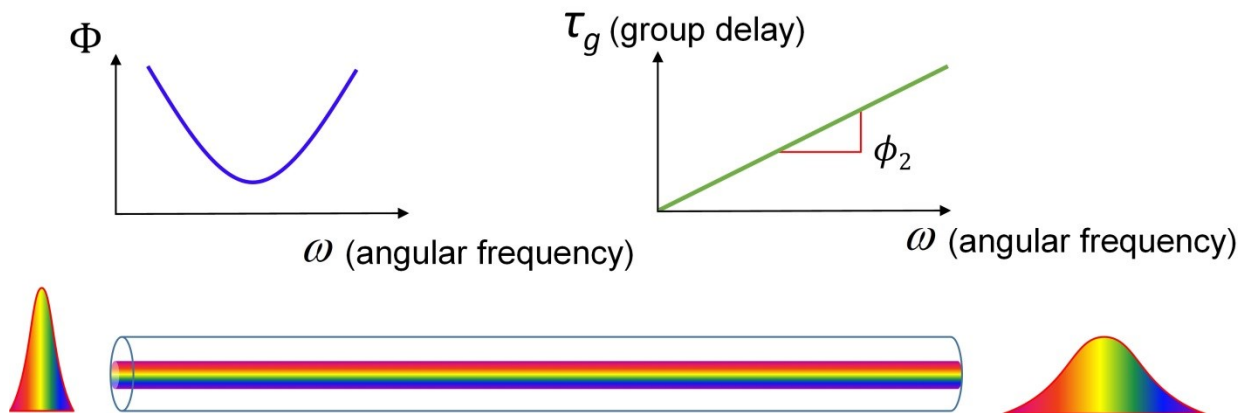


Figure 1.7 - Effet d'élargissement des impulsions par propagation linéaire à travers un milieu dispersif du premier ordre.

Mathématiquement, la propagation linéaire à travers un milieu diélectrique, par exemple un guide d'onde ou une fibre optique monomode, peut généralement être modélisée comme un système linéaire invariant dans le temps (LTI, pour 'linear time-invariant'), ou un filtre linéaire, caractérisé par une fonction de transfert spectral de la forme $H(\omega) = |H(\omega)| \exp(j\phi(\omega))$, où $|H(\omega)|$ est une constante qui tient compte des pertes ou atténuations pendant la propagation (sans importance pour notre propos) et $\phi(\omega) = \beta(\omega) \times z$, avec β étant la constante de propagation du mode et z étant la distance de propagation [58]. Les effets de la dispersion des fibres sont expliqués en développant la constante de propagation de mode en une série de Taylor autour de la fréquence ω_0 autour de laquelle le spectre d'impulsion de propagation est centré [58]

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \frac{1}{6} \beta_3(\omega - \omega_0)^3 + \dots \quad (1.2)$$

où

$$\beta_m = \left[\frac{\partial^m \beta}{\partial \omega^m} \right]_{\omega=\omega_0} \quad (m=0, 1, 2, \dots) \quad (1.3)$$

Les paramètres β_1 et β_2 sont liés à l'indice de réfraction et ses dérivés à travers les relations

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c} \left(n + \omega \frac{dn}{d\omega} \right), \quad (1.4)$$

$$\beta_2 = \frac{1}{c} \left(2 \frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2} \right), \quad (1.5)$$

Où n_g est l'indice de groupe et v_g est la vitesse du groupe. Le terme de premier ordre β_1 , est l'inverse de la vitesse de groupe, c'est-à-dire le retard de groupe par unité de longueur. Physiquement parlant, il représente la vitesse de l'enveloppe d'une impulsion optique, tandis que le terme de second ordre β_2 représente la dispersion de la vitesse du groupe et est responsable de l'élargissement de l'impulsion. Ce phénomène est généralement appelé *dispersion de vitesse de groupe* (GVD pour group velocity dispersion), et β_2 le paramètre de GVD.

En plus de ces deux paramètres, le coefficient β_3 apparaissant dans Eq. (1.2) est appelé le paramètre de dispersion du troisième ordre (TOD, pour third-order dispersion), il conduit à des distorsions supplémentaires de l'impulsion optique ultracourte dans les régimes de propagation linéaire [59] et non linéaire [35]. Ce terme de dispersion d'ordre supérieur peut être ignoré dans la discussion suivante, car son effet est négligeable pour la plupart des milieux et structures diélectriques conventionnels (par exemple, fibres optiques), en supposant que les formes d'onde optiques qui s'y propage présentent des variations temporelles dans le régime picoseconde ou plus.

En l'absence d'effets dispersifs d'ordre supérieur, en considérant les deux premiers termes du développement de Taylor du milieu dispersif dans l'équation. (1.2), la fonction de transfert de phase spectrale est approximée par une fonction quadratique, appelée l'approximation de dispersion du premier ordre. Dans ces conditions, le retard de groupe du milieu dispersif, défini comme $\tau_0 = \frac{d\Phi(\omega)}{d\omega} = \phi_1 + \phi_2(\omega - \omega_0)$, présente une variation linéaire en fonction de la fréquence. La dispersion caractéristique du premier ordre du milieu est déterminée par la pente du retard de groupe en fonction de ω , ϕ_2 , appelé coefficient de dispersion du premier ordre.

Comme décrit ci-dessus, le coefficient de dispersion du premier ordre est ensuite lié au paramètre GVD par $\phi_2 = \beta_2 \times Z$, où nous rappelons à nouveau que Z est la distance de propagation à travers le milieu dispersif.

Pour compléter la description de la propagation des impulsions à travers un milieu dispersif de premier ordre, nous rappelons ici un modèle mathématique équivalent largement utilisé. La propagation d'une impulsion d'amplitude complexe, centrée autour d'une fréquence porteuse, le long d'un milieu dispersif de premier ordre est décrite par l'équation suivante [58]:

$$\frac{\partial A}{\partial z} = \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} \quad (1.6)$$

où la variable t est décrite dans un repère qui se déplace à la vitesse de groupe du support de propagation. Dit autrement, Eq. (1.6) ignore le retard de groupe à travers le système, car cela représente simplement un retard global de l'impulsion de propagation (dispersée). Fait intéressant, l'équation (1.6) est mathématiquement équivalente à l'équation d'onde paraxiale qui régit la diffraction de la lumière continue [1] et en particulier, elle devient identique à cette équation lorsque la diffraction se produit dans une seule direction transversale et β_2 est remplacée par $-\lambda/2\pi$, où λ est la longueur d'onde de la lumière. Cette similarité mathématique est à la base de la théorie de la dualité espace-temps, qui permet d'établir des analogies formelles entre les effets et les processus spatiaux et temporels [60]. L'équation (1.6) est facilement résolue en utilisant la méthode de transformée de Fourier avec l'approximation d'enveloppe lentement variable, ce qui suppose que l'amplitude $A(z, t)$ varie lentement avec z sur l'échelle d'un cycle optique. Si $\tilde{A}(z, \omega)$ est la transformée de Fourier de $A(z, t)$ de telle sorte que

$$A(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{A}(z, \omega) \exp(i\omega t) d\omega \quad (1.7)$$

la solution d'Eq. (1.6) est donné par

$$\tilde{A}(z, \omega) = \tilde{A}(0, \omega) \exp\left(\frac{i}{2} \beta_2 \omega^2 z\right) \quad (1.8)$$

L'équation (1.8) montre que la GVD modifie la phase de chaque composante spectrale de l'impulsion d'une quantité qui dépend de la fréquence et de la distance propagée. De l'équation (1.8), nous pouvons définir la fonction de transfert spectral linéaire du milieu dispersif de premier ordre, comme suit

$$H(\omega) \propto \exp(j\Phi(\omega)) = \exp\left(j\frac{\beta_2\omega^2 z}{2}\right) = \exp\left(j\frac{\phi_2\omega^2}{2}\right) \quad (1.9)$$

C'est la fonction de transfert qui a été définie ci-dessus pour modéliser un milieu dispersif de premier ordre, ignorant simplement le terme linéaire de $\phi(\omega)$, β_1 . Nous rappelons encore que ce terme représente un retard temporel et n'affecte pas la forme de l'impulsion, il peut être négligé dans les discussions en cours sans perte de généralité. Pour résumer, un milieu dispersif du premier ordre peut être décrit à travers une fonction de transfert spectral linéaire qui présente une réponse d'amplitude constante et une phase spectrale quadratique dans le domaine fréquentiel. Des exemples de milieux de dispersion largement utilisés dans le contexte des communications optiques et des applications apparentées comprennent les fibres optiques, les réseaux de Bragg sur fibres à pas linéairement variable (LC-FBG), les prismes, et les réseaux de diffraction [1, 14, 61].

1.4.2 Auto-imagerie (ou effet Talbot) temporelle induite par la dispersion

L'effet Talbot temporel se réfère à la création d'auto-images d'un train de forme d'onde périodique (par exemple d'impulsions) quand celui-ci se propage à travers un milieu dispersif de premier ordre dans des conditions spécifiques bien établies. L'effet Talbot temporel est l'équivalent temporel de l'effet Talbot spatial; l'effet est observé lorsqu'un train périodique de formes d'ondes optiques (par exemple, des impulsions), avec une période de répétition T , se propage à travers un milieu dispersif (DM, pour 'dispersive medium') sous l'approximation de dispersion du premier ordre. Comme on peut le voir sur la figure 1.8, lorsque les impulsions temporelles périodiques se propagent à travers le milieu dispersif, une fibre optique par exemple, elles commencent à s'élargir jusqu'à ce que leurs ailes se chevauchent (non représentées sur la figure, pour plus de clarté). À ce stade, les impulsions sont typiquement inutiles parce qu'elles ne conservent pas leur caractéristiques individuelles, un processus qui affecte négativement le transfert d'information. Cependant, lorsque la propagation continue, les impulsions élargies dans le train d'impulsions commencent à interférer avec les impulsions adjacentes et dans une condition spécifique, c'est-à-dire aux distances dites de Talbot, le train d'impulsions d'entrée original sera exactement répliqué. C'est l'effet d'auto-imagerie temporelle entière. En plus de cet effet, à certaines distances fractionnaires, le train d'impulsions d'origine réapparaît mais avec un taux de répétition qui est un multiple entier de l'original. C'est l'effet d'auto-imagerie temporelle fractionnaire.

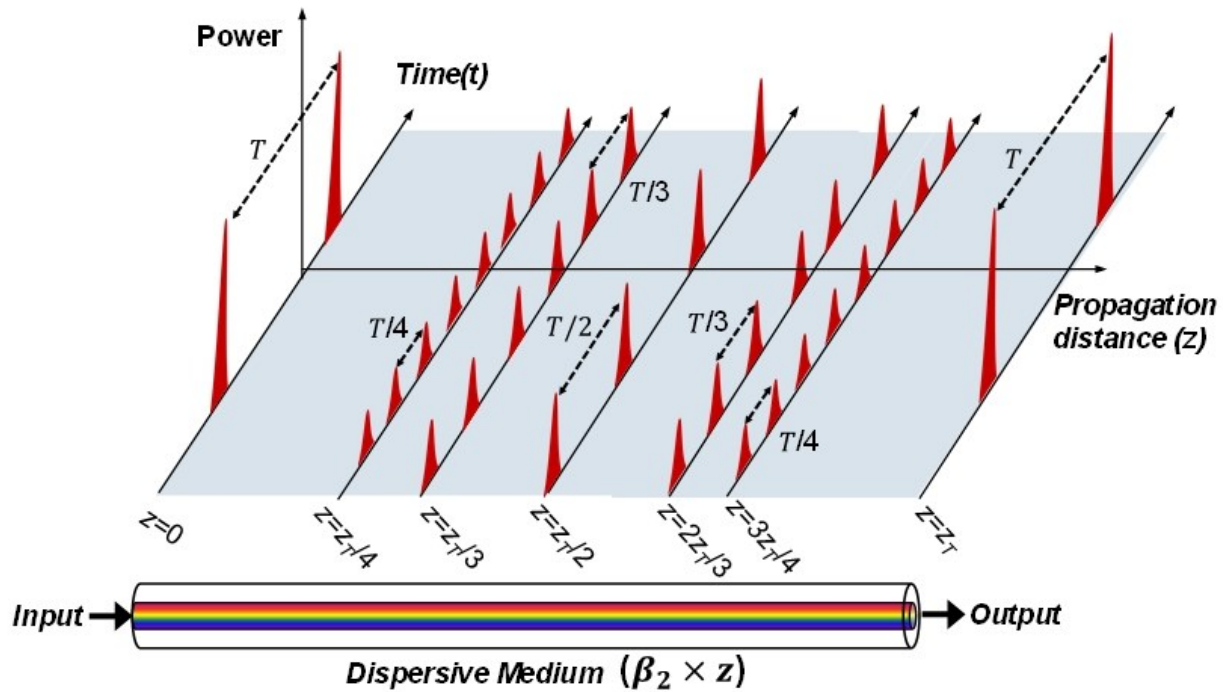


Figure 1.8 - Effet Talbot temporel. Évolution d'un train d'impulsions périodique par propagation le long d'un milieu dispersif de premier ordre.

La figure 1.8 représente l'évolution d'un train d'impulsions périodique qui se propage le long d'un milieu dispersif de premier ordre; en accord avec les descriptions ci-dessus, on suppose un tronçon de fibre optique, où la pente du retard de groupe augmente linéairement avec la distance de propagation z , c'est-à-dire $\phi_2 = \beta_2 \times z$. Pour une description mathématique plus formelle, supposons que l'enveloppe complexe du signal périodique d'entrée $A_{in}(t)$, représentée sur la figure 1.8 à $Z = 0$ (où Z représente la coordonnée de propagation axiale), peut être exprimée comme

$$A_{in}(t) = A(t, z = 0) = \sum_{p=-\infty}^{\infty} a_0(t - pT) \quad (1.10)$$

où T est la période de répétition et $a_0(t)$ est une forme temporelle arbitraire dans chaque période dans l'intervalle $|t| \leq T/2$, et $a_0 = 0$, pour $|t| > T/2$. La puissance optique moyenne correspondante pour ce train d'impulsions d'entrée peut être définie comme $P_{in(t)} = |A_{in}(t)|^2$.

Comme mentionné ci-dessus, la propagation linéaire à travers un milieu dispersif sous l'approximation de la dispersion du premier ordre peut être exprimée par la fonction de transfert spectral dans Eq. (1.9). En utilisant une approche basée sur la théorie des signaux pour tous les cas de l'effet Talbot (effets entier et fractionnaire) [1], le spectre d'enveloppe complexe

$\tilde{A}_{out}(\omega)$ de l'impulsion de sortie $A_{out}(t)$ peut être obtenu en multipliant directement le spectre de l'enveloppe complexe $\tilde{A}_{in}(\omega) = F\{A_{in}(t)\}$ et la fonction de transfert $H(\omega)$ dans l'Eq. (1.9)

$$\tilde{A}_{out}(\omega) = \tilde{A}_{in}(\omega) \times H(\omega) \quad (1.11)$$

Rappelons que sous l'approximation de dispersion de premier ordre, la valeur de dispersion augmente linéairement avec la distance de propagation z ($\phi_2 = \beta_2 \times z$). Par conséquent, pour différentes distances de propagation inférieures à z , nous pouvons observer différentes formes en sortie. Par exemple, sur la fig.1.8, le train d'impulsions d'entrée à la distance $z=0$ est auto-imagé exactement après propagation le long d'un milieu dispersif à une distance $z = s \times z_T$ où z_T est la distance Talbot entière définie comme

$$z_T = \frac{T^2}{2\pi\beta_2} \quad (1.12)$$

et avec $s = 1, 2, 3, \dots$ etc.

Pour les valeurs paires de s ($= 2, 4, 6, \dots$), le signal de sortie est une réplique exacte du signal d'entrée. Pour les valeurs impaires de s ($= 1, 3, 5, \dots$), le signal d'origine est également reproduit mais avec un décalage d'une demi-période $T/2$. En résumé, à des distances de fibre qui sont à un multiple entier de la distance de base de Talbot $z_T = T^2/2\pi\beta_2$, les répliques exactes du signal d'entrée sont reproduites soit avec une synchronisation exacte par rapport au train d'impulsions d'entrée, ou avec un retard supplémentaire égale à la moitié de la période d'origine (effet Talbot entier inversé). En plus des images de reconstruction décrites, on trouve d'autres motifs intéressants. En particulier, à des distances fractionnaires données par

$$z = \frac{s}{m} z_T = \frac{s}{m} \frac{T^2}{2\pi\beta_2} \quad (1.13)$$

avec $s = 1, 2, 3, \dots$, $m = 2, 3, 4, \dots$, avec (s/m) un nombre rationnel non entier et irréductible, le signal de sortie est une copie du signal d'entrée périodique (où chaque impulsion individuelle conserve sa forme et sa largeur temporelle), mais avec un taux de répétition multiplié m fois. Dans ce cas, la puissance d'impulsion de sortie individuelle est réduite de manière correspondante par le facteur m , en ignorant les pertes d'insertion potentielles du milieu dispersif. La figure 1.8 montre des exemples de trains d'impulsions de sortie aux distances de Talbot fractionnaires où le taux de répétition d'entrée a été multiplié par des facteurs $m = 4, 3$ et 2 , respectivement. Ce processus de multiplication du taux de répétition ne modifie que le taux de répétition de l'intensité du signal, tandis que l'amplitude spectrale du signal reste inchangée.

Cela se traduit par une phase temporelle résiduelle impulsion-à-impulsion déterministe sur le train d'impulsions de sortie. Cette phase temporelle résiduelle indique le cas où l'amplitude du champ de forme d'onde est avancée ou retardée par rapport au centre de l'enveloppe. Cette caractéristique sera discutée plus en détail plus loin dans cette section. Il convient également de mentionner que le taux de répétition maximum en sortie est limité à la largeur d'impulsion d'entrée. Cette dernière doit être suffisamment courte pour que les impulsions ne se chevauchent pas sur le train de sortie multiplié; plus précisément, en supposant que la condition de Talbot est satisfaite, alors $m \leq D_{out-max} T/t_{in}$ où t_{in} est la largeur d'impulsion d'entrée et $D_{out-max}$ est le rapport cyclique maximal des impulsions de sortie avant le chevauchement d'impulsions [62].

Afin de présenter le principe de l'effet Talbot temporel de manière plus intuitive, nous pouvons utiliser des représentations conjointes temps-fréquence (TF) des signaux impliqués, comme le montre la figure 1.9. Pour chaque représentation TF, l'axe du bas représente la variation temporelle du train d'impulsions et l'axe de gauche représente le spectre correspondant, la distribution d'énergie 2D étant représentée dans la courbe centrale. La figure 1.9 (a) montre un exemple lorsque l'effet Talbot entier est considéré (c'est-à-dire, $m = 1$). Dans ce cas, le milieu dispersif, avec un coefficient ($\phi_2 = \beta_2 \times Z = T^2/2\pi$) introduit un retard de groupe T entre deux composantes de fréquence discrètes adjacentes avec un espacement de fréquence de $F (= 1/T)$, c'est-à-dire, $\Delta\omega = 2\pi/T$. Ainsi, les composantes spectrales du train d'impulsions d'entrée sont inclinées vers différentes positions temporelles par le retard de groupe du milieu de dispersion et sont à nouveau distribuées par la période d'impulsion d'entrée T . La superposition spectrale du train d'impulsions dispersées reproduit l'image du train d'impulsions d'origine à la sortie de la fibre, comme illustré à la figure 1.9 (a).

La figure 1.9 (b) montre le cas où le signal d'entrée est un train d'impulsions périodiques et nous visons un facteur de division du taux de répétition égal à 2 (Eq. (1.13) avec $s = 1, m = 2$). Le coefficient de dispersion est fixé à $\frac{\phi_2}{2} = \beta_2 \times \frac{Z}{2} = \frac{T^2}{4\pi}$ et introduit un retard de groupe de $T/2$ entre deux composantes de fréquence discrètes adjacentes avec un espacement de fréquence original de $F (= 1/T)$. Similaire au mécanisme précédent, chaque composante spectrale est inclinée vers différentes positions temporelles et redistribuée dans les nouvelles positions temporelles entre les composantes fréquentielles adjacentes, conduisant à la création prédite de nouvelles impulsions avec une période temporelle de $T/2$, comme le montre la figure 1.6 (b).

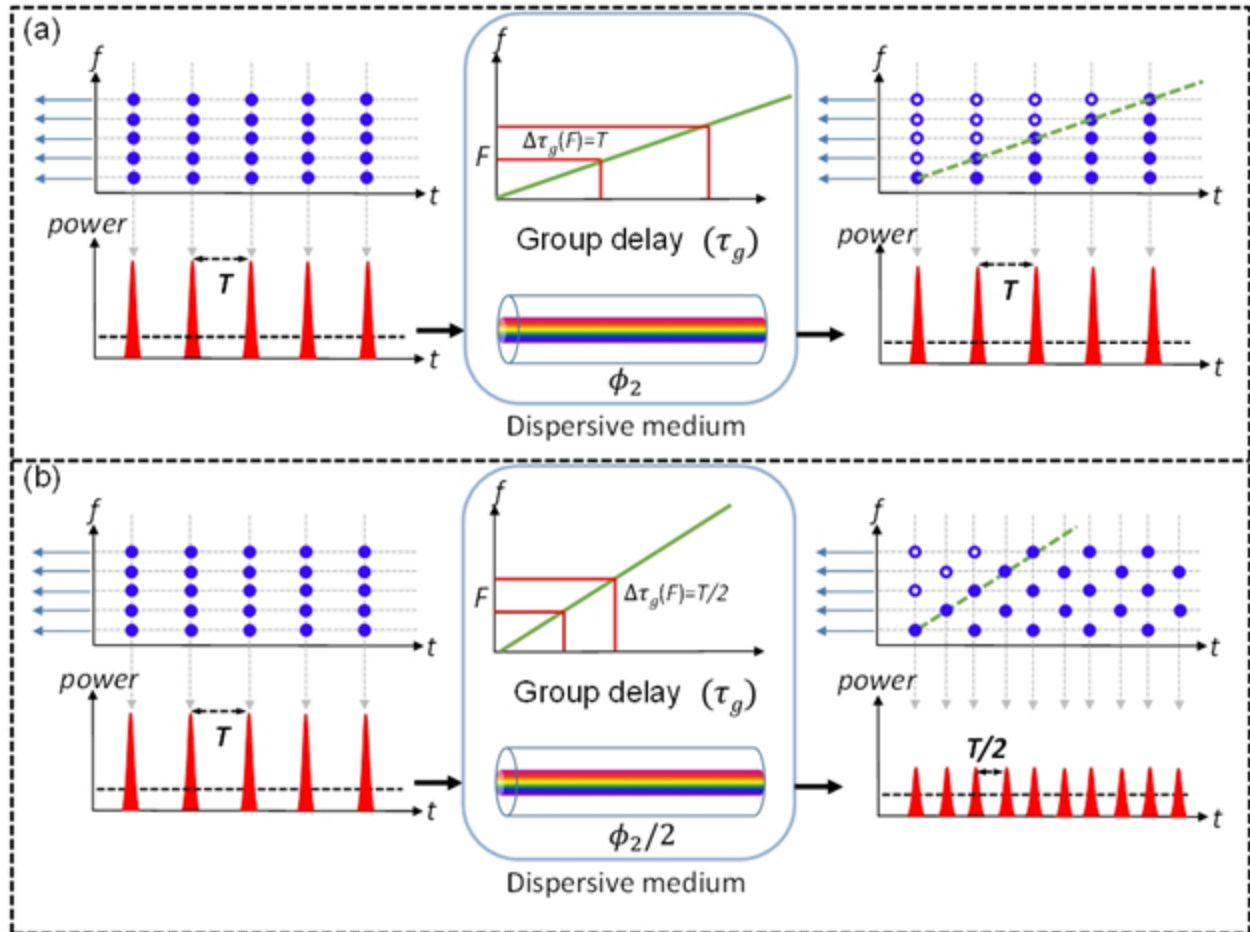


Figure 1.9 - Analyse conjointe temps-fréquence de l'effet Talbot temporel. t: temps, f: fréquence.

Jusqu'à présent, nos discussions ont porté sur les distributions d'intensité temporelle des trains d'impulsions produites par l'effet Talbot temporel; cependant, il y a une autre caractéristique importante à discuter dans ce qui suit. Comme mentionné ci-dessus, les trains d'impulsions dont le taux de répétition a été multiplié par l'effet Talbot fractionnaire présentent des variations déterministes de la phase temporelle résiduelle d'impulsion à impulsion. Ces variations de phase fournissent un outil puissant pour le contrôle et la manipulation des trains d'impulsions de sortie qui peuvent être produits par effet Talbot.

Comme le montre la figure 1.10, dans une auto-image de Talbot entière, le profil de phase uniforme de l'entrée est restauré, comme on peut le voir, par exemple, dans les impulsions auto-imagées à la distance z_T . Notez que dans cette illustration, les profils de phase temporelle des trains d'impulsions résultants sont représentés par les lignes bleues en pointillés. Cependant, les auto-images des trains dont le taux de répétition a été multiplié sont affectées par une phase résiduelle déterministe d'impulsion à impulsion, comme celles observées à $z_T/3$

et $z_T/2$. La phase résiduelle pour une image fractionnaire particulière peut être calculée analytiquement pour s et m donnés [63].

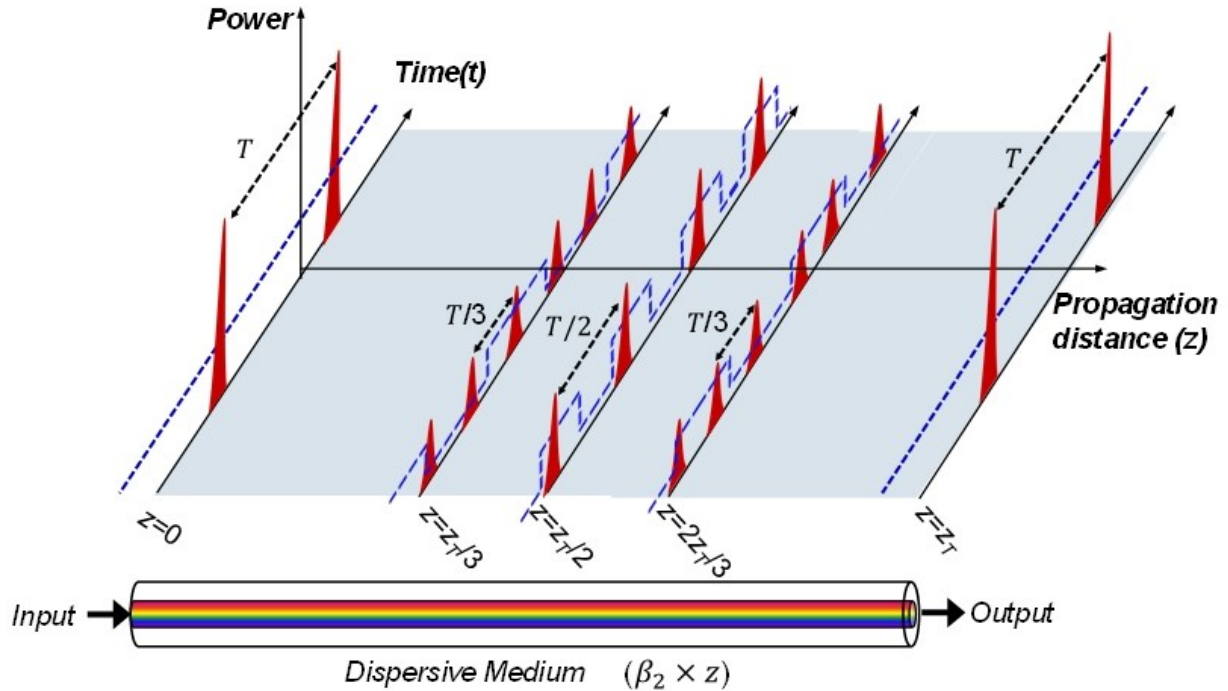


Figure 1.10-Effet Talbot temporel. Evolution d'un train d'impulsions périodiques par propagation le long d'un milieu dispersif de premier ordre et les variations de phase temporelle résiduelle des trains d'impulsions résultantes (représentées par les lignes bleues en pointillés).

Plus précisément, la fonction de phase de la n -ième impulsion d'une image fractionnaire particulière, pour m et s donnés, est définie par l'équation suivante [63]

$$\varphi_n = -\frac{s}{m} \left(\left[\frac{1}{s} \right]_m \right)^2 \pi n^2 \quad (1.14)$$

quand $s \cdot m$ est pair, et

$$\varphi_n = -2(s/m) \left[\frac{1}{2} \right]_m \left(\left[\frac{1}{2s} \right]_m \right)^2 \pi (2n+m)^2 \quad (1.15)$$

quand $s \cdot m$ est impair. Dans ces équations, $\left[\frac{1}{a} \right]_b$ est l'inverse de a modulo b . s, m sont co-premier avec m ($= 2, 3, 4, \dots$), et $n = 0, 1, 2, \dots$ est le nombre d'impulsion. Notez que les profils de phase discrets définis dans Eq. (1.14) et Eq. (1.15) sont périodiques avec une période fondamentale égale à m , à savoir, les fonctions de phase temporelle définies dans l'équation

(1.14) et (1.15) montrent une dépendance quadratique avec la position d'impulsion, identifiée par le facteur n . Ce comportement est en réalité équivalent à l'effet d'une modulation de phase quadratique temporelle continue et crée m fois plus de fréquences dans le spectre du signal d'entrée, avec un espacement de fréquence réduit de m fois par rapport à l'entrée. Ceci est connu comme l'effet d'auto-imagerie spectrale [64]. Si ces déphasages sont réduits à une plage de 2π , une séquence périodique d'étapes de phase discrètes dans la plage $[0, 2\pi]$ est obtenue.

1.4.3 Auto-imagerie temporelle inverse conventionnelle (I-TSI)

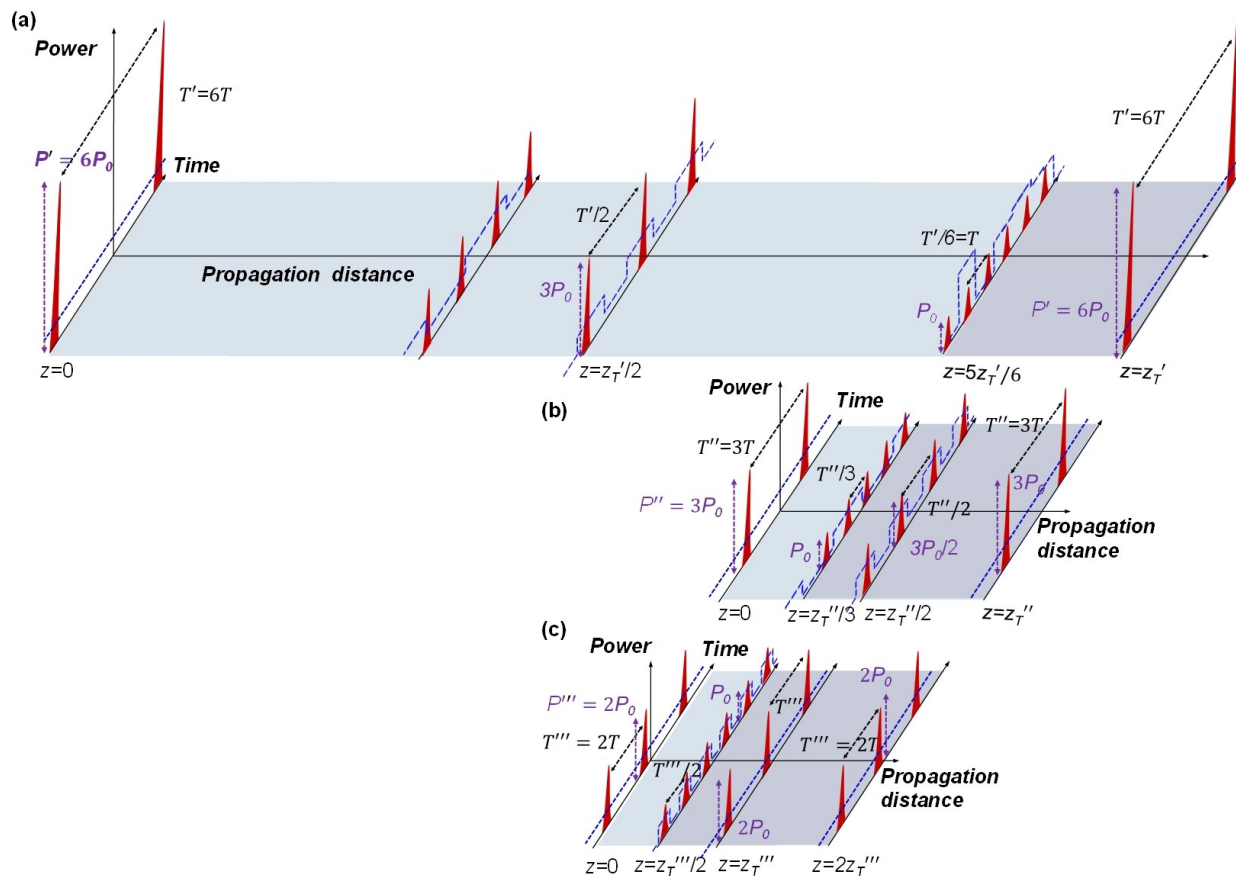


Figure 1.11- L'effet Talbot temporel standard. Évolution d'un train d'impulsions périodiques par propagation le long d'un milieu dispersif de premier ordre. (a) Tapis de Talbot pour une période de répétition d'entrée $T' = 6T$ (b) $T'' = 3T$ (c) $T''' = 2T$.

Le I-TSI est l'effet inverse de l'effet d'auto-imagerie (ou Talbot) temporelle (TSI), dans lequel l'image temporelle finale amplifiée est récupérée à partir d'une auto-image dont le taux de répétition a été multipliée précédemment. Comme le montre la Fig. 1.11, en haut, dans l'effet Talbot temporel standard, une forme d'onde répétitive à phase plane (signal à $Z = 0$) est auto-imagé, après propagation dispersive sur une distance z_T' (distances Talbot entière). Il existe

également une infinité de distances fractionnaires, définies par le "tapis de Talbot" [1, 11, 55, 56, 65], où l'on peut observer des auto-images du train d'ondes d'entrée avec un taux de répétition multipliées (effet Talbot fractionnaire), avec une intensité de forme d'onde individuelle correspondante réduite. Les exemples dans la figure 1.11 (a) aux distances de Talbot $z_T'/2$ et $z_T'/6$ ont des intensités réduites par les facteurs par lesquels le taux de répétition est multiplié, $m = 2$ et $m = 6$, respectivement. Dans une auto-image de Talbot entière, le profil de phase uniforme de l'entrée est restauré, comme on peut le voir par exemple dans les impulsions auto-imaginées à une distance z_T' dans le tapis supérieur (profils de phase représentés par les lignes bleues en pointillés). Cependant, les auto-images aux taux de répétitions multipliées sont affectées par une phase résiduelle déterministe d'impulsion à impulsion, comme celles observées à $z_T'/2$ et $5z_T'/6$.

Dans les conceptions originales de l'effet I-TSI, comme proposé initialement pour l'amplification de Talbot [18], il a été proposé de prétraiter un train d'impulsions d'entrée pour imiter le taux de répétition et la phase temporelle des auto-images avec un taux multipliées, e.g., à $z_T'/2$ et $5z_T'/6$ dans l'exemple spécifique montré à la Fig. 1.12. En propageant ces trains d'impulsions à la distance de Talbot la plus proche z_T , l'intensité du train d'impulsions est amplifiée par la quantité de réduction du taux de répétition. Dans les cas où les entrées prétraitées correspondent au train d'impulsions à $z_T'/2$ et $5z_T'/6$, les facteurs d'amplification du train de sortie sont respectivement $m = 2$ et $m = 6$ (le cas de l'amplification par $m = 6$ est montré dans Fig. 1.12).. Suivant cette stratégie de conception, le milieu dispersif doit introduire une valeur de dispersion totale qui augmente linéairement avec le facteur m de division du taux de répétition, ou d'amplification d'impulsions [18]

$$\phi_2 = \beta_2 z = m \frac{T^2}{2\pi} \quad (1.16)$$

où je rappelle que m est le facteur d'amplification ou facteur de division, T est la période de répétition du train d'impulsions d'entrée, z est la longueur du milieu dispersif et β_2 est le coefficient de dispersion, défini comme la pente du retard de groupe en fonction de la fréquence radiale, par unité de longueur. Les principes de fonctionnement des travaux rapportés dans les réf. [3, 18] sont basés sur le concept d'auto-imagerie temporelle inverse (I-TSI), impliquant une combinaison de modulation de phase et de dispersion, comme celle introduite pour la première fois dans la réf. [18], représenté sur la Fig.1.12. Le travail précédent basé sur la conception I-TSI pour l'amplification de Talbot [18] a montré avec succès des résultats expérimentaux d'amplification passive, avec un facteur de gain $m = 2, 5, 15$ et 27 à la sortie de la fibre

implémenté avec une fibre optique monomode. En particulier, une dispersion totale de $\sim 2.650 \text{ ps / nm}$ a été utilisée dans le cas de $m = 2$ et $m = 5$ (en modifiant le taux de répétition du train d'impulsions d'entrée pour correspondre aux conditions de Talbot nécessaires) et de $\sim 8000 \text{ ps / nm}$ pour $m = 15$ et $m = 27$ (encore une fois, en modifiant la fréquence d'impulsion d'entrée pour qu'elle corresponde aux conditions de Talbot correspondantes). En outre, l'effet I-TSI sur des trains d'impulsions aperiodiques a aussi été démontré et étudié [3]. Dans cette référence, les auteurs ont rapporté l'extraction des signaux d'horloge sous-harmonique de 4,85 GHz, 3,23 GHz et 2,43 GHz ainsi que l'horloge de fréquence de base de 9,7 GHz à partir d'un signal de données RZ-OOK avec PRBS de $9,7 \text{ Gbit/s } 2^7 - 1$. Les valeurs de dispersion correspondantes utilisées pour la démonstration sont $\sim 2647 \text{ ps/nm}$, $\sim 3972 \text{ ps/nm}$ et $\sim 5294 \text{ ps/nm}$ pour les ordres sous harmoniques (SH-CR) de $m = 2, 3$ et 4 , respectivement. Ainsi, selon les conceptions I-TSI originales [3, 18], chaque facteur d'amplification ou facteur de division de débit nécessite une nouvelle valeur de dispersion, typiquement mise en œuvre en changeant physiquement l'élément dispersif (bobine de fibre, réseau de Bragg, etc.).

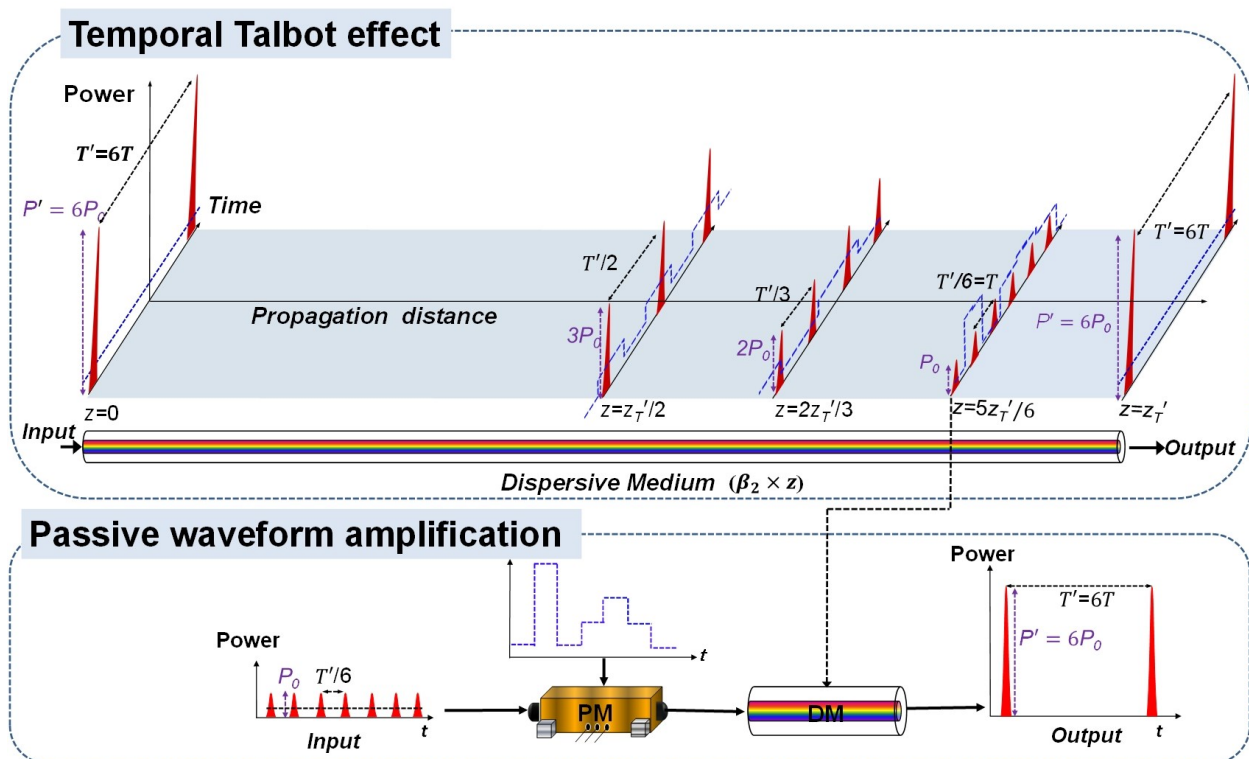


Figure 1.12 - La conception originale de l'amplificateur de Talbot conventionnel. L'addition cohérente de formes d'onde périodiques est obtenue en adaptant la phase temporelle du train d'onde d'entrée et la propagation subséquente à travers un milieu dispersif de sorte que l'intensité de forme d'onde individuelle (énergie) est amplifiée par une réduction du taux de répétition. Adapté de la Réf. [18].

1.4.4 Conception généralisée pour I-TSI

La contribution centrale de cette thèse est un nouvel ensemble généralisé d'équations de conception pour induire l'effet I-TSI. Cette stratégie de conception innovante permet de régler le facteur de division du taux de répétition, ou d'amplification d'impulsions, en modifiant simplement le profil de modulation de phase temporelle, sans modifier la quantité de dispersion. Dans ce but, nous introduisons une généralisation non triviale des équations de dispersion qui permettent d'induire un effet I-TSI désiré (équations de conception pour la dispersion et les signaux de modulation de phase), conduisant à une gamme relativement large de facteurs d'amplification d'impulsions, pour une dispersion fixe, en programmant de manière appropriée l'étape de modulation de phase temporelle. La stratégie de conception généralisée au cœur de ce travail est décrite plus en détail au chapitre 2. Un résumé de cette stratégie est présenté ci-dessous.

La figure 1.11 montre le concept de réalisation de facteurs programmables d'amplification d'impulsions ou de division de fréquence en utilisant le même milieu dispersif. L'idée peut être comprise à travers une comparaison des trois différents tapis de Talbot représentés sur la figure 1.11 (a), la figure 1.11 (b) et la figure 1.11 (c), chacun correspondant à une période de répétition d'entrée différente, $T' = 6T$, $T'' = 3T$ et $T''' = 2T$. Tous les tapis présentent le même taux de répétition, T , aux distances de Talbot fractionnaires $5z_T'/6$, $z_T''/3$, et $z_T'''/2$ respectivement. Si nous prétraitons un train d'impulsions d'entrée pour correspondre aux formes d'onde à ces distances fractionnaires (même période, T , mais différentes phases temporelles résiduelles), la propagation à travers le même retard dispersif (représenté par un ombrage violet dans les tracés) donne un train d'impulsions de sortie à phase plane avec des facteurs d'amplification $m = 6$, $m = 3$ et $m = 2$, respectivement. Dans cet exemple, la même distance de propagation dispersive requise pour les deux facteurs d'amplification est donnée par $\frac{z_T'}{6} = \frac{2z_T''}{3} = \frac{3z_T'''}{2} = \frac{T'}{(12\pi\beta_2)}$. La clé de la conception proposée est que, pour assurer la même longueur de propagation dans les trois cas, nous sélectionnons le premier plan de Talbot entier ($q = 0$, où q est un paramètre libre pour numérotter le plan entier utilisé) dans le tapis supérieur, et le premier plan entier de Talbot ($q = 0$) dans le tapis du milieu, mais le troisième plan Talbot entier ($q = 1$) dans le tapis inférieur.

Cet exemple fournit les directives nécessaires pour obtenir les équations généralisées basées sur l'effet I-TSI pour la division du taux de répétition (ou l'amplification d'impulsions) d'un train d'onde d'entrée, avec une période de répétition égale à T , par un facteur de division (ou gain d'amplification) m ($= 2, 3, 4, \dots$). Pour ces dérivations, nous supposons que l'emplacement

général du plan d'entrée dans le tapis de Talbot est à $(s/m)z_T$, où z_T est la distance fondamentale de Talbot correspondant à une période d'entrée égale à m fois la période T , ($T_0 = m \times T$), nous rappelons que s est un entier et co-prime avec m . De même, l'emplacement général du plan de sortie est à $(q + 1)z_T$, avec $q = 0, 1, 2, \dots$. Le train de forme d'onde d'entrée doit être modulé en phase selon la fonction de modulation de phase de Talbot correspondant à l'emplacement d'entrée $(s/m)z_T$ dans le tapis, en utilisant Eq. (1,14) et (1,15) [64]. Par la suite, le train d'impulsions modulé doit se propager à travers la quantité de dispersion suivante

$$\phi_2 = (qm + m - s)mT^2/2\pi \quad (1.17)$$

À ce stade, il convient de mentionner que choisir $s = m - 1$ et $q = 0$ (premier plan de Talbot entier) dans les équations généralisées Eq. (1.17) et Eq. (1.14, 1.15) donne lieu à l'équation de dispersion classique ($\phi_2 = \frac{mT^2}{2\pi}$), Eq. (1.16), et l'application du profil de modulation de phase temporel ($\varphi_n = (m - \frac{1}{m})\pi n^2$) précédemment défini pour l'amplification conventionnelle de Talbot basée sur I-TSI, comme indiqué dans [18].

Pour en revenir à notre stratégie de conception généralisée, considérons maintenant la situation où nous choisissons un facteur de gain maximum $m = M$. La valeur de dispersion requise correspondante en mettant $q = 0$ et $s = M - 1$ est $\varphi_2 = MT^2/2\pi$. En effet, pour une période temporelle d'entrée prescrite T , on peut maintenant utiliser cette même valeur de dispersion pour une gamme plus large de facteurs de gain, satisfaisant $\varphi_2 = (qm + m - s)mT^2/2\pi = MT^2/2\pi$, selon Eq. (1.17) ci-dessus. Dans cette équation, s et q sont des paramètres de conception libres, et en tant que tels, nous pouvons obtenir un certain nombre de différents facteurs de gain m , plus petits ou égaux à M ($m \leq M$), qui satisfont cette condition pour s et q donnés. Les fonctions de modulation de phase requises peuvent ensuite être obtenues en utilisant Eq. (1.14) et (1.15) avec les facteurs m et s correspondants.

Dans une configuration pratique pour traiter des trains de formes d'ondes optiques, le processus de modulation de phase temporelle peut être mis en œuvre en utilisant une modulation électro-optique, où le signal optique est modulé par une forme d'onde électronique. Le dernier peut être généré à partir d'un générateur de forme d'onde arbitraire (AWG, pour 'arbitrary waveform generator'), qui peut être facilement programmé pour produire le profil de modulation souhaité. Ceci est la base des conceptions programmables électroniquement, proposées dans mon mémoire de Maîtrise pour (i) l'amplification passive de formes d'onde optiques répétitives et (ii) la récupération de l'horloge sous-harmonique à partir de signaux de données de télécommunication RZ-OOK, tous deux basés sur l'I-TSI.

1.4.5 Considérations sur les implémentations pratiques de I-TSI

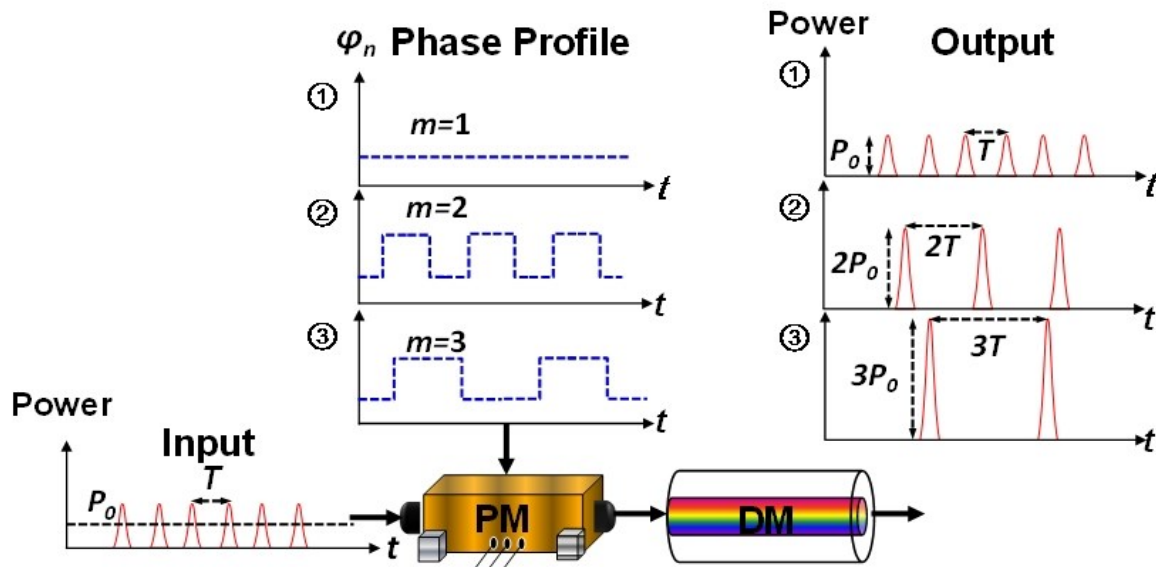


Fig. 1.13 - Méthode de prétraitement de phase des trains d'impulsions pour l'effet I-TSI programmable pour induit par dispersion. PM: modulateur de phase. DM: milieu dispersif.

Rappelons que le I-TSI est une ingénierie inverse de l'effet TSI, dans lequel l'image temporelle amplifiée finale est récupérée à partir d'une auto-image précédente multipliée par le débit. L'effet I-TSI sur les formes d'onde optiques peut être mis en œuvre en utilisant une combinaison de modulation de phase électro-optique et un milieu dispersif à fibres optiques, par exemple, comme le montre la figure 1.13. Dans mon travail, le milieu dispersif a été mis en œuvre à l'aide d'un LC-FBG fonctionnant en réflexion [1]. Ceci est créé par photo-inscription d'une perturbation périodique de l'indice de réfraction le long du noyau d'une fibre monomode de telle sorte que la période de la perturbation est à pas linéairement variable le long de la longueur du dispositif. Cela se traduit par différentes fréquences (fréquences de Bragg) réfléchies à différentes positions le long du dispositif de réseau, la fréquence réfléchie changeant linéairement le long de la longueur du dispositif, conduisant à une courbe de retard de groupe qui dépend linéairement de la variable de fréquence. En tant que tel, de manière similaire à tout dispositif dispersif du premier ordre, un LC-FBG réfléchissant peut être décrit par une fonction de transfert spectral linéaire qui présente une réponse d'amplitude constante et une phase spectrale quadratique dans le domaine fréquentiel. Un LC-FBG peut être conçu pour fournir une très grande dispersion, c'est-à-dire équivalente à la dispersion fournie par des centaines de kilomètres d'une fibre optique monomode conventionnelle, sur une très large bande passante (facilement de quelques THz, suffisante pour couvrir la bande passante des formes d'onde

temporelles de résolution picoseconde), et dans un format très compact, avec une longueur aussi courte que quelques dizaines de centimètres. Un LC-FBG doit être exploité en réflexion de sorte qu'il doit être incorporé dans un dispositif supplémentaire (par exemple un circulateur) pour récupérer les signaux réfléchis. Un inconvénient bien connu d'un LC-FBG est qu'il peut présenter des ondulations de retard de groupe qui peuvent affecter la propagation d'une impulsion à large bande. Afin de minimiser l'effet des ondulations de retard de groupe dans le LC-FBG utilisé dans nos expériences, la bande passante d'impulsion d'entrée a été réduite à $\sim 0,200$ nm (25 GHz) avec un filtre passe-bande de type gaussien augmentant ainsi la largeur d'impulsion à l'entrée de l'amplificateur Talbot à ~ 17 ps (intensité pleine largeur à mi-hauteur, FWHM pour 'full width at half maximum').

Avant le filtrage de la phase spectrale grâce à la propagation dispersive, une phase temporelle appropriée est ajoutée à travers un modulateur de phase électro-optique. Rappelons qu'il s'agit d'un dispositif permettant de moduler la phase temporelle d'une onde optique entrante en fonction du profil de tension électrique appliqué sur un cristal électro-optique [66]. Pour une performance de modulation optimale, la polarisation du champ électrique de l'onde optique d'entrée doit être réglée correctement pour correspondre aux propriétés du cristal électro-optique. Actuellement, des modulateurs de phase électro-optiques pour la modulation de signaux optiques à des vitesses proches de 100 GHz sont disponibles sur le marché [67]. L'intensité de la forme d'onde optique de sortie sera localement amplifiée en fonction du facteur de réduction du taux de répétition qui est induit par le profil de modulation de phase temporelle. Dans notre travail, la modulation de phase temporelle multiniveaux requise pour un facteur d'amplification souhaité a été appliquée aux impulsions optiques en utilisant un modulateur de phase électro-optique fibré (bande passante de 40 GHz) piloté par un générateur électronique de formes d'onde arbitraire. (Tektronix AWG7122C, avec 7.5 GHz de bande passante). Bien que ce générateur fournisse le niveau de phase prescrit sur un intervalle égal à la période de répétition des impulsions, nous notons que cette technique nécessite seulement la phase constante correcte sur la largeur d'impulsion, ceci permet une haute tolérance aux erreurs dans le signal de modulation de phase. Cela nous a permis d'utiliser un AWG de 7.5 GHz pour manipuler efficacement un signal de 19.2 GHz, impulsion par impulsion.

Comme mentionné précédemment, les principes de fonctionnement des travaux rapportés dans les réf. [3, 18] et nos travaux actuels sont tous basés sur le concept d'effet I-TSI, impliquant une combinaison de modulation de phase et de dispersion, comme introduit pour la première fois dans la réf. [18]. Cependant, dans les conceptions précédentes, un facteur de gain différent nécessite l'utilisation d'une quantité différente de dispersion (changement du

milieu dispersif), le système est donc réglé pour réaliser un facteur d'amplification fixe, et qui ne peut pas être facilement réglé après. Dans notre travail, nous sommes capables, à travers l'introduction d'une généralisation non triviale des équations basées sur I-TSI (équations de conception pour les phases de modulation de phase et de dispersion), d'obtenir une gamme relativement large de facteurs de gain ou de division de fréquence utilisant une dispersion fixe, qui peut être reconfigurable électriquement en programmant de manière appropriée l'étape de modulation de phase temporelle dans un dispositif modulateur électro-optique. Les profils de modulation de phase temporelle nécessaires peuvent être pré-calculés par l'équation généralisée nouvellement établie pour l'effet I-TSI dans Eq. (1.17). La programmabilité peut être obtenue en utilisant une ligne dispersive à fibre optique (ou un réseau de Bragg sur fibre à pas linéairement variable), grâce à une reconfiguration électronique de la tension d'alimentation de pilotage du modulateur électro-optique.

CHAPTER ONE: INTRODUCTION

1.1 Background and Motivation

The temporal self-imaging effect (TSI) has been drawing attention and attracting researchers over the past decade. TSI, also referred to as temporal Talbot effect, is the time-domain counterpart of the well-known spatial self-imaging phenomenon [1-3]. Temporal imaging systems and temporal self-imaging (Talbot) phenomena are examples of applications of space-time duality theory. Fig. 1.1 shows the schematic diagram of the space-time duality between spatial and temporal self-imaging effects [4]. TSI occurs when a periodic train of optical pulses propagates through a dispersive medium in a first-order approximation; such a dispersive medium is characterized by a linear all-pass amplitude response and a quadratic phase variation along with frequency. An appropriate amount of the first-order dispersion, given by the so-called self-imaging condition [1, 2], leads to either an exact reproduction of the original pulse train (integer TSI, shown in Fig. 1.1) or to repetition-rate multiplication by an integer factor (fractional TSI). These interesting features of TSI enable to meet recent demands from emerging applications, particularly for optical telecommunication. In fact, the intrinsic physical properties of the TSI phenomenon have been employed for many important applications.

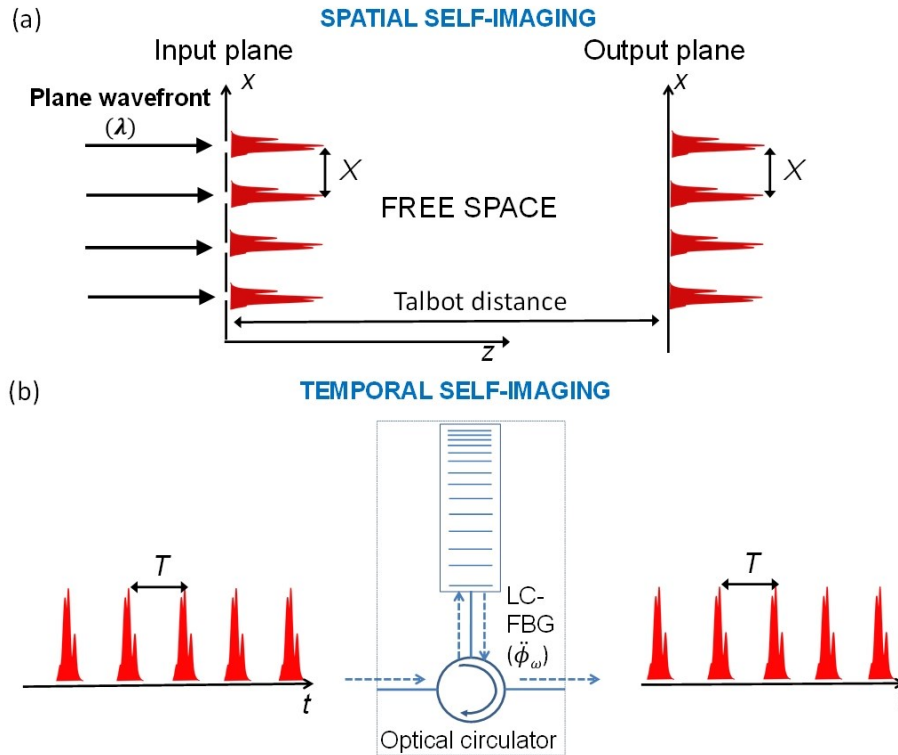


Figure. 1.1-Schematic diagram of the space-time duality (a) Spatial equivalent of the self-imaging. (b) Temporal equivalent of the self-imaging. The representations show the case of the integer self-imaging effect. Adapted from Ref. [4].

- Fractional TSI has been extensively studied for achieving repetition-rate multiplication of a periodic pulse train in a lossless manner [5-10]. Most typically, either single-mode fibers (SMFs) [11-13] or linearly chirped fiber Bragg gratings (LC-FBGs) [2, 14-15] have been used as dispersive media for practical implementations.
- This phenomenon has been theoretically investigated for accurately measuring the first-order dispersion coefficient of a dispersive medium [2].
- The inherent buffering ability of TSI has been demonstrated to generate a periodic output, even from an aperiodic input pulse train. This property has been used for recovering the base-rate (BR) clock signal from aperiodic data streams, e.g., with a return-to-zero on-off keying (RZ-OOK) format, in a lossless fashion [16-17]. Again, SMFs and LCFBGs have been used as practical alternatives for implementation of the required dispersive media [2, 11-15].

- More recently, a new feature of TSI, namely inverse temporal self-imaging (I-TSI), has been demonstrated to enable dividing the repetition rate of the incoming periodic waveform by a desired factor in a lossless fashion [18-19]. I-TSI involves the use of a suitably designed temporal phase modulation step before the first-order dispersive medium. I-TSI is the foundation of a simple, all-fiber based noiseless passive amplification technique for repetitive optical signals without using active gain [18]. Fig. 1.2(a) provides an illustration of the I-TSI scheme as utilized for passive amplification of repetitive waveforms [18].
- The passive amplifier based on I-TSI has the ability to mitigate temporal noise present on the input signals, such as reduction of pulse-to-pulse intensity fluctuations and timing jitter [20]. As an extension of this interesting property, I-TSI has been used for sub-harmonic clock recovery (SH-CR) from pulsed telecommunication data signals, i.e., with a clock rate that is divided by a desired factor with respect to the symbol rate of the incoming data [3]. Fig. 1.2(b) provides an illustration of the SH-CR application of the I-TSI scheme [3].

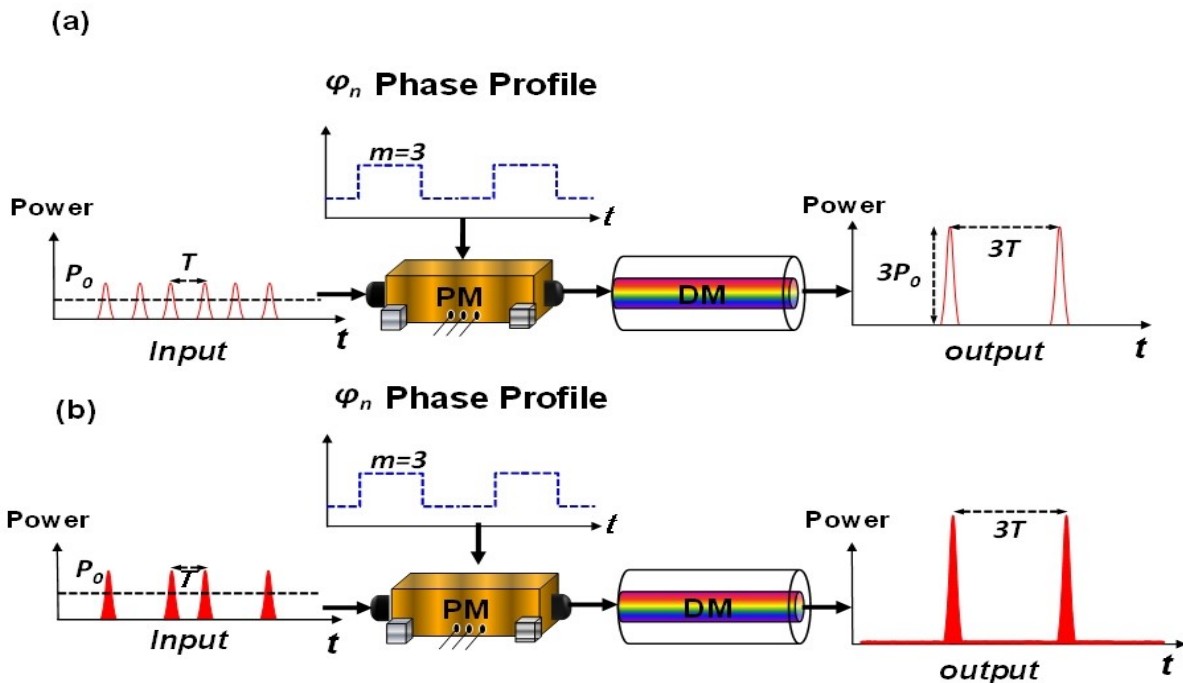


Figure 1.2- Method for phase preconditioning pulse trains for dispersion-induced I-TSI effect. PM: phase modulator. DM: dispersive medium (a) Talbot passive amplification (b) SH clock recovery from an on-off-key (OOK) data modulated pulse train.

One of the main applications of dispersion-induced TSI is for optical pulse repetition-rate multiplication [10]. Interestingly, it has been proved that the rate multiplication factors can be programmed by incorporating a temporal phase modulation step before the dispersive medium, in such a way that a variety of rate multiplication factors can be achieved by suitably programming the phase modulation pattern in the system [10]. Electronic reconfigurability of the optical pulse rate multiplication process is possible by use of electro-optic phase modulation, in which the incoming optical pulse train is modulated by an electronic signal, e.g., as generated from an electronic arbitrary waveform generator (AWG) [10]. In contrast, conventional designs for Talbot amplification [18], and the related SH-CR circuits [3], are unable to provide any electronic programmability, i.e., to be able to tune the system key specifications, namely the gain factor for the Talbot amplifier or rate-division factor for the Talbot SHCR circuit.

The work in this thesis targets the design and demonstration of a programmable Talbot passive amplifier and a programmable SH-CR circuit. These two blocks exploit a reverse engineering design of the TSI, referred to as I-TSI [3, 18]. As mentioned above, this requires the use of a temporal phase modulation step before the dispersive medium to induce a lossless repetition-rate division process. Nevertheless, in previous reported designs [3, 18], a different amount of dispersion is required to achieve a different rate-division factor, i.e., a different gain factor for the Talbot amplifier or a different clock-rate division factor for the SH-CR circuit. Consequently, the conventional I-TSI design approach does not allow for tuning (and hence programmability) the gain factor or the clock-rate division factor, without physically changing the dispersive element, a substantial, unpractical modification. Obviously, as for any amplifier device, the capability of tuning the gain factor is critical for practical applications of the amplifier. In addition, recovering the clock signal from an optical data signal with a programmable rate provides an additional important versatility in the telecommunication or signal-processing platform at hand.

In this work, I report a non-trivial generalization of the I-TSI equations (i.e., design equations for the desired phase modulation and dispersive stages), which allow us to obtain a relatively wide tuning range of the repetition-rate division factor (or equivalent pulse gain factor) using a fixed dispersion, by suitably programming the temporal phase modulation imparted on the pulse train. Electronic programmability of gain in the Talbot amplifier, or the rate of the recovered clock in the SH-CR circuit, is then possible and demonstrated herein through the use of an electro-optic phase modulation stage, as illustrated in Fig.1.3 for the Talbot amplifier case.

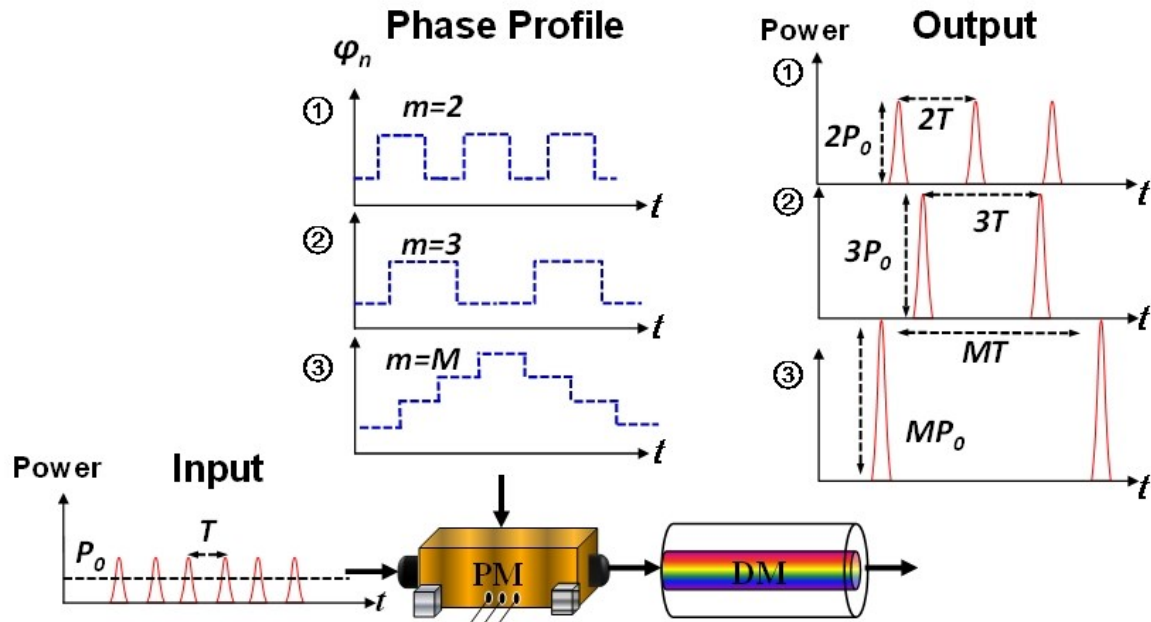


Figure 1.3-Programmable method for phase preconditioning pulse trains for programmable dispersion-induced I-TSI. PM: phase modulator. DM: dispersive medium.

1.2 Research Problems and Objectives

Signal amplification is essential in telecommunication systems for the compensation of accumulated power losses, as induced by a variety of signal related processes and propagation. Furthermore, there are various applications requiring high intensity optical pulses, including nonlinear microscopy [21], optical computing and material processing [22]. Various types of optical amplifiers have been demonstrated in the past such as the erbium-doped optical fiber amplifier (EDFA) [23], the semiconductor optical amplifier (SOA) [24], the fiber Raman amplifier (FRA) [25], etc. All these amplifiers are based on *active gain* mechanisms, where the signal is amplified directly by multiplying the signal carriers through a process that is fed by an external source [26-33]. It is undisputable that the EDFA is particularly relevant in the context of long haul optical communication system. Still, an EDFA requires using an external source to feed the active gain process in order to amplify a signal. Compared to the EDFA solution, the SOA is advantageous in terms of energy efficiency [34]. However, this type of amplifiers still suffer from critical shortcomings, such as high noise, low gain, polarization dependence and high nonlinearity with fast transient time. As for the Raman amplifier, the principle of FRA is based on Raman gain, which results from the effect of stimulated Raman scattering [35]. Due to the

Raman effect, FRA presents some important limitations, e.g., related with high pump power requirements and sophisticated gain control.

Figure 1.4 shows a simple example of a conventional active amplification process, here exemplified through an EDFA. The circuit is composed of the active-gain medium and a pump laser, a key requirement in all active amplification process. In addition, employment of active amplification typically contributes amplitude and phase noise, such as amplified spontaneous emission (ASE) noise or timing-jitter [36-37], and may induce other signal distortions due to the limited-gain frequency bandwidth provided by the amplifier. Since the active gain process inherently amplifies pre-existing noise from the input source as well as it adds its own noise into the signal, the output signal-to-noise ratio (SNR) essentially degrades [18]. This imposes a degradation of the noise figure, which is a common figure-of-merit of any active amplifier, defined as the ratio of the SNR of the input signal to the SNR of the output signal [38]. Although phase-sensitive amplifiers have been shown capable of realizing low-noise amplification (with experimental noise figures as low as 1 dB [33]), these involve the use of complex and inefficient nonlinear processes. Generally, the amplification of weak signals by conventional amplifiers typically renders the signal totally undetectable due to the amplification and injection of noise [18].

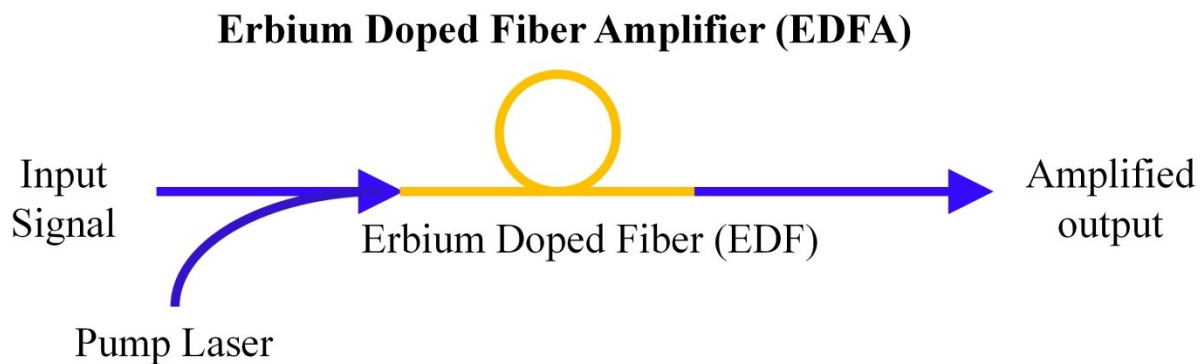


Figure 1.4- Active amplification setup: Erbium Doped Fiber Amplifier setup schematic.

On another note, as far as the applications involving high-peak power pulse generation [21-22, 39] are concerned, traditional active amplification is extremely inefficient. In order to generate high-peak power optical pulses, many pulses in a wave-train are intentionally thrown away, 'pulse picking,' either prior to amplification [40] or during the amplification process (regenerative amplification) [41], to concentrate energy from the external source in fewer remaining output pulses.

In order to overcome the described drawbacks above, *passive* amplifiers have been demonstrated in the past to amplify *repetitive input waveforms* (e.g. optical pulses) without using

an active gain medium through coherent waveform addition [42-43]. However, the coherent addition of many identical waveforms is extremely challenging. Figure 1.5 shows the operational principle of conventional passive amplification process. In this scheme, a repetitive input waveform train is stored and coherently added to itself in a high-finesse cavity, building up into fewer, amplified waveforms at the output. Thus, these methods require very accurate phase control of the input signal envelope and the carrier, including carrier envelope phase stabilization, in order to stabilize the input waveform in the cavity such that each pulse is constructively added into the amplified output. Such requirements are often impractical outside of a laboratory environment. Specifically, small phase shifts in each pulse tend toward destructive interference.

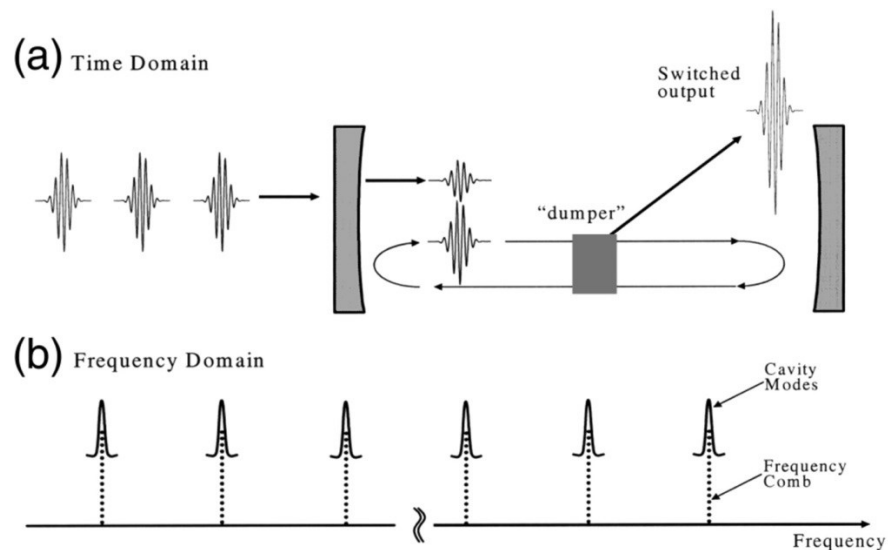


Figure 1.5-Coherent pulse amplification with the aid of an optical cavity.

Recently, our group reported a simple and novel, all-fiber passive amplification technique for repetitive waveforms without using active gain processes [18]. Figure 1.6 illustrates the concept of the Talbot passive waveform amplification technique, which exploits the intrinsic coherence revival times of periodic waveform trains provided by passive dispersive broadening, known as temporal ‘self-imaging’ or the temporal Talbot effect [1] (illustrated in Fig. 1.6, top). In particular, passive amplification is achieved by effectively redistributing and coherently adding the overall input energy of a repetitive waveform signal into fewer waveforms, resulting in each output individual waveform to be an amplified replica of the input. To implement this, we effectively exploit an “inverse temporal self-imaging effect (I-TSI)” in which the final amplified temporal image is recovered from a previous multiplied self-image [18]. The passive Talbot amplifier

provides the desired amplified replica of an incoming input optical pulse train without distorting individual pulse characteristics by applying a simple combination of temporal phase modulation and a dispersive medium. In contrast to traditional pulse coherent-addition methods [42], the Talbot technique implements a similar process without using the additional resonant cavity and the stringent timing and stabilization conditions associated with it. The only condition is that the input waveform is repetitive and should maintain its coherence over the output repetition rate. Because the passive Talbot amplification technique is based upon the fundamental process of linear superposition of waves, this can be applied to any systems using repetitive signals, including regions of the electromagnetic spectrum or other wave-based platforms for which active gain processes for waveform amplification are limited or do not exist.

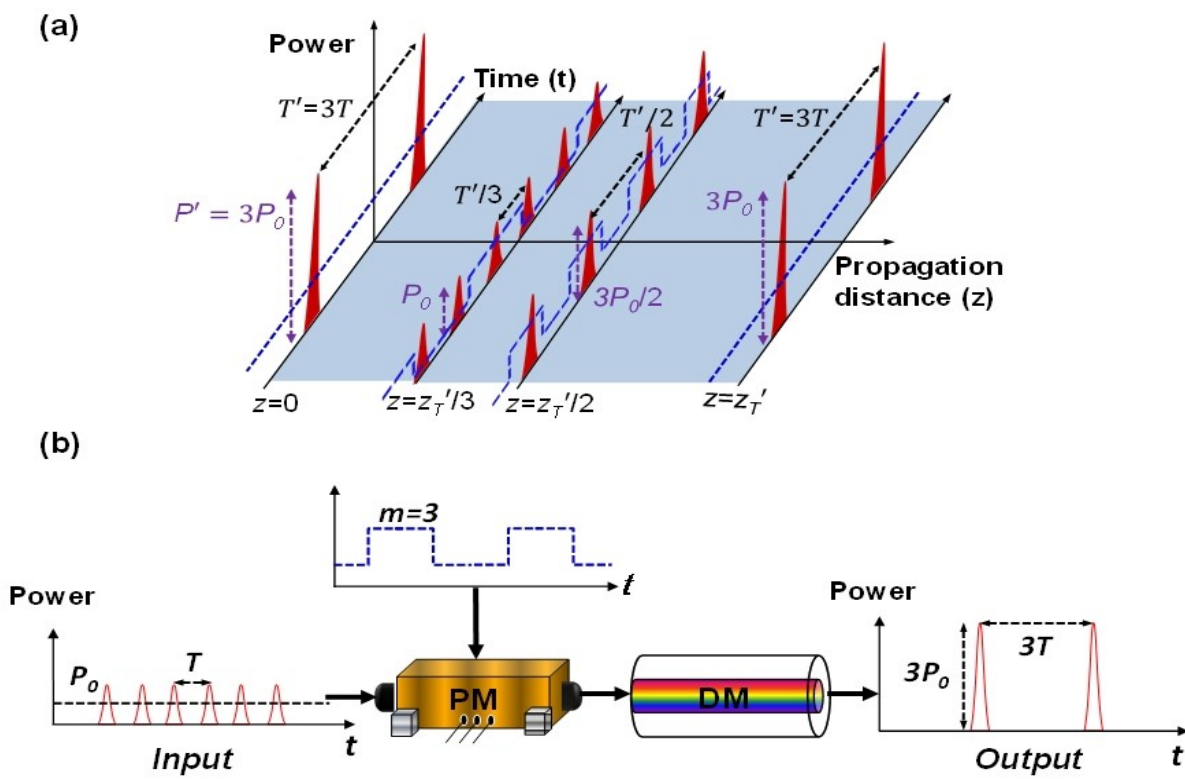


Figure 1.6-(a) Standard temporal Talbot effect, illustrating the evolution of a repetitive input pulse train through propagation along a first-order dispersive medium. (b) Talbot passive waveform amplification concept (PM: phase modulator, DM: dispersive medium).

Despite these diverse advantages of the above mentioned Talbot passive amplification, there is a main limitation in regards to tuning the gain factor, which is a key capability of any amplifier. As discussed, the previous work employed a fixed length of dispersive medium for a given gain factor, which inherently requires different dispersive media in order to modify the gain factor. This represents a significant –eventually, unpractical- modification in the experimental

setup, limiting the flexibility of this previous design to achieve a desired gain value. Therefore, in this Thesis, I propose and experimentally demonstrate an adapted generalized version of Talbot passive amplification in which the gain factor can be electrically reconfigurable. Similarly to the previous design [18], the amplifier setup is composed of an electro-optic phase modulator followed by an optical dispersive medium. By generalizing the equations for the required phase modulation and dispersion to induce a desired I-TSI effect, we are able to obtain a range of various gain factors using a fixed dispersion, i.e., without changing the dispersive medium. Our proof-of-concept experiments have successfully demonstrated in-fiber amplification of picosecond optical pulses with tunable gain factors from 2 to 30, using a linearly chirped fiber-Bragg grating (LC-FBG) as a dispersive medium.

In addition to this work, the newly proposed design based on I-TSI can be employed for a programmable base-rate or sub-harmonic (BR/SH) clock recovery circuit. Extracting the timed clock from the received optical signals, known as optical timing extraction, is also a feature of great significance in the context of synchronous operations in high-speed optical telecommunication system. In particular, base-rate clock recovery (BRCR) is indispensable for many key functions such as 3R regeneration [44], and general signal processing techniques [45]. Additionally, sub-harmonic clock recovery (SHCR) (repetition rate reduction with respect to the original data's base rate) is an interesting technique that allows for recovering an optical clock for synchronization at a lower rate. Generally, the SH clock can be manipulated with lower-frequency electronics, a feature that is generally interesting and of particular interest to perform de-multiplexing and subsequent signal-processing operations in optical time-division multiplexed (OTDM) systems [46-49]. It has already been reported that the base-rate and sub-harmonic clock signals can be recovered from a Return-to-Zero On-Off-Keying (RZ-OOK) optical data signal in a lossless fashion by exploiting the TSI effect [1-2]. Indeed, TSI is a unique physical principle that enables a single platform for generation of both clock signals. In particular, Pudo et al. introduced the inherent buffering ability of TSI to generate a periodic output, even from an aperiodic input pulse train, and this has been used for performing base-rate clock recovery (BRCR) for a RZ-OOK optical data signal by using single-mode fibers (SMFs) or linearly chirped fiber Bragg gratings (LC-FBGs) as a dispersive medium [16-17]. Related to this work, Reza et al. further demonstrated how the I-TSI effect can be also exploited to generate a periodic output (with a divided, i.e., sub-harmonic, repetition rate) from an aperiodic input pulse train, a property that could be used for recovering the corresponding sub-harmonic clock signal (SHCR) from a RZ-OOK data signal [3]. Nonetheless, using this SHCR scheme, which employs a fixed length of dispersive medium for a given bit rate division factor, it is therefore not

straightforward to tune the division factor without changing the dispersive element- a significant system reconfiguration. A new design for programmable BR/SH clock recovery has been numerically investigated and experimentally demonstrated in this Thesis, in which the clock rate division factor can be electrically reconfigurable. Similar to the programmable amplifier setup, the proposed clock recovery setup is composed by an electro-optic phase modulator followed by a fiber-optics dispersive medium. As mentioned above, through the generalization introduced here on the equations for I-TSI, the desired rate division factor is readily tunable by programming the phase modulation function. A proof-of-concept experimental demonstration and numerical analysis of the proposed reconfigurable SHCR technique are reported on an 11.1 Gbit/s RZ-OOK data signal.

1.3 Thesis organization

The ongoing Chapter 1 introduces a comprehensive background for the temporal Talbot effect, in which the theoretical analysis of the effect and its fundamental properties are explained. In particular, the main scheme for implementation of the proposed design concepts for the programmable Talbot amplifier and the programmable BR/SH clock recovery is introduced. The proposed scheme exploits a reverse-engineering of the conventional Talbot effect, which is referred to as “inverse temporal self-imaging (I-TSI) effect”, to achieve energy-preserving repetition-rate division of an incoming periodic arbitrary waveform (e.g., pulse) train. As such, the proposed scheme employs a combination of temporal phase modulation (e.g., implemented through electro-optic phase modulation) and fiber-optics dispersion to process the incoming periodic waveform train. We introduce here the basis of our proposed generalization of the I-TSI equations, which enables realization of a programmable Talbot amplification process and a programmable BR/SH clock recovery process. This novel, generalized I-TSI design allows us to obtain different rate division factors with a fixed dispersive medium by suitably programming the temporal phase modulation step.

In Chapter 2, I provide the detailed derivation of the generalized I-TSI equations; to validate the proposed principle, this chapter presents results on a programmable passive amplification process based on the generalized I-TSI effect, where the output pulse intensities can be electrically reconfigurable without changing the dispersive medium.

Chapter 3 focuses on the application of the generalized I-TSI theory to construct a programmable BR/SH clock recovery circuit, where sub-harmonic clock signals and the base-

rate clock signal are successfully extracted from a 2^7-1 PRBS 11.1Gbit/s data signal without changing the dispersive medium, in an electrically reconfigurable manner.

Chapter 4 summarizes the work reported in this Thesis and suggests potential future perspectives.

1.4 The Temporal Talbot Effect

The Talbot effect, also referred to as self-imaging or lensless imaging is a near field diffraction effect that has been observed with light in optics [43, 50-53], see Fig. 1.1, top plot. When a plane wave is incident through a grating or other periodic structure, the resulting wave front propagates in such a way that it replicates the structure at multiples of a certain defined distance, known as the Talbot length. The Talbot Effect was first discovered by its namesake, Henry Fox Talbot, in the mid-eighteen hundreds. He worked to produce images that would stay fixed on a piece of paper. These experiments resulted in his fame, as he is now known as one of the inventors of photography [54]. During his studies he observed the remarkable effect that now carries his name. When he examined a coarsely ruled diffraction grating with a simple magnifying lens, Talbot noticed that the grating image would reappear as he moved the glass out of focus. If illuminated by white light, it would split into different colors, and monochromatic light would cause the image to come into focus at multiples of a particular distance. Talbot published the results of some of his experiments on the subject in 1836, but did not pursue the subject further, as he was investing his time and money into photography. After a half century later, the Talbot effect was rediscovered by Lord Rayleigh in 1881. Rayleigh explained it as a natural consequence of Fresnel diffraction, and showed that the Talbot length z_T is given by

$$z_T = \frac{a^2}{\lambda} \quad (1.1)$$

where a is the period of the grating and λ is the wavelength of the incident light. He also mentioned that the Talbot effect could have a practical application to reproduce gratings by exposing film to one of the revival images behind the original grating [50]. Chronologically, the phenomenon of Talbot effect based on classical diffraction theory was later rediscovered by Winkelmann [51], Weisel [52], and Wolfke [53] at the beginning of the last century, as they tried to figure out grating image formation in microscopy. In the mid-1950s, Cowley and Moodie made an intensive study of the properties of the Fresnel diffraction field behind periodic objects,

where they found the grating structure is replicated at multiples of a certain longitudinal distance, z_T .

The well-known duality between the paraxial diffraction of optical beams in the spatial domain and the temporal distortion of narrowband pulses in a dispersive medium has been widely studied to introduce and establish temporal analogs of spatial systems [55]. Due to the mathematical analogies between spatial diffraction and temporal dispersion, the time-domain equivalent of the spatial Talbot effect, the so-called temporal Talbot effect, was first described by T. Jansson and J. Jansson in 1981 [56]. The temporal Talbot effect occurs when a temporally periodic optical signal propagates through a dispersive medium under first-order dispersion condition [56], see illustration example in Fig. 1.1(b). Jansson and Jansson found the fiber distances at which an input repetitive signal is exactly reproduced. Since then, the temporal Talbot effect has attracted remarkable interest [1-2, 11, 57]. A central motivation comes from the fact that the temporal Talbot effect can be used for multiplying the repetition rate of a periodic input pulse train without distorting the individual pulse features (such as the pulse temporal profile and duration) by simple, linear propagation of the original pulse train through a first-order dispersive medium (e.g., a piece of conventional optical fiber) [11-13]. The rate multiplication is produced fundamentally without losing any of the input pulse energy (except for potential practical passive losses in the dispersive medium).

1.4.1 Temporal chromatic dispersion

Before going into the details of the temporal Talbot effect, it is worth describing “the dispersive medium” term, which is the key component for realization of the temporal Talbot effect. When an electromagnetic wave interacts with the bound electrons of a dielectric, the medium response, in general, depends on the optical (radial) frequency ω . This property, referred to as chromatic dispersion, manifests through the frequency dependence of the refractive index $n(\omega)$ [58]. The effect is for instance observed when light propagates through an optical waveguide composed of dielectric materials (e.g., an optical fiber). In this particular case, chromatic dispersion is a consequence of the frequency dependence of the refractive indices of the involved dielectrics (material dispersion) as well as the frequency dependence of the light beam propagation properties, e.g., propagation angle (waveguide dispersion) [58], so that the overall effect is then characterized through the frequency dependence of an effective refractive index, referred here to as $n(\omega)$ for simplicity and to ensure the generality of the presented formulation.

Fiber dispersion plays a critical role in the propagation of short optical pulses [58] because different spectral components associated with the pulse travels at different speeds, given by $c/n(\omega)$, where c is the speed of light in free space and $n(\omega)$ is the frequency dependence of the refractive index. Even when the nonlinear effects are not important, dispersion-induced pulse broadening can be detrimental for optical communication systems [58], see figure 1.7.

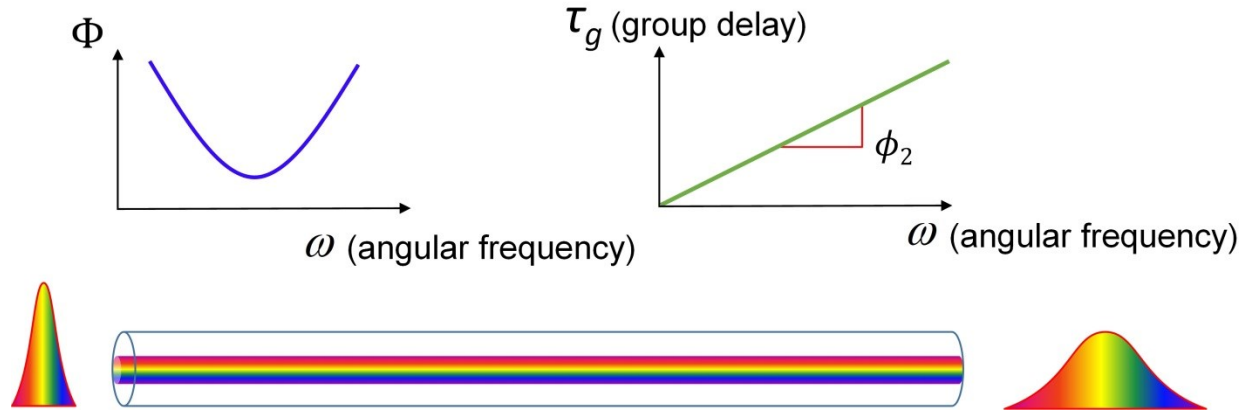


Figure 1.7-Pulse broadening effect by linear propagation through a first-order dispersive medium.

Mathematically, linear propagation through a dielectric medium, e.g., a single-mode optical waveguide or fiber, can be generally modeled as a linear time-invariant (LTI) system, or a linear filter, characterized by a spectral transfer function of the form $H(\omega) = |H(\omega)| \exp(j\Phi(\omega))$, where $|H(\omega)|$ is a constant that accounts for losses or attenuation during propagation (of no importance for our purposes) and $\Phi(\omega) = \beta(\omega) \times z$, with β being the mode-propagation constant and z being the propagating distance [58]. The effects of fiber dispersion are accounted for by expanding the mode-propagation constant β in a Taylor series around the frequency ω_0 at which the propagating pulse spectrum is centered [58]:

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \frac{1}{6} \beta_3(\omega - \omega_0)^3 + \dots \quad (1.2)$$

where

$$\beta_m = \left[\frac{\partial^m \beta}{\partial \omega^m} \right]_{\omega=\omega_0} \quad (m=0, 1, 2, \dots) \quad (1.3)$$

The parameters β_1 and β_2 are related to the refractive index $n(\omega)$ and its derivatives through the relations

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c} \left(n + \omega \frac{dn}{d\omega} \right), \quad (1.4)$$

$$\beta_2 = \frac{1}{c} \left(2 \frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2} \right), \quad (1.5)$$

where n_g is the group index and v_g is the group velocity. The first-order term, β_1 , is the inverse of the group velocity, v_g , i.e., *the group delay per unit length*. Physically speaking, it represents the speed of the envelope of an optical pulse, while the second-order term parameter, β_2 represents the dispersion of the group velocity and is responsible for pulse broadening. This phenomenon is usually referred to as *group-velocity dispersion* (GVD), and β_2 is the GVD parameter.

In addition to these two parameters, the coefficient β_3 appearing in Eq. (1.2) is called the third-order dispersion (TOD) parameter, leading to additional distortions of the propagating ultrashort optical pulse both in the linear [59] and nonlinear regime [35]. This higher-order dispersion term can be ignored in the following discussion, since its effect is negligible for most conventional dielectric media and structures (e.g., optical fibers), assuming that the propagating optical waveforms exhibit time variations in the picosecond regime or longer. In the absence of higher-order dispersive effects, considering the first two terms of the Taylor expansion of the dispersive medium in Eq. (1.2), the spectral phase transfer function $\Phi(\omega)$ is approximated by a quadratic function, and this is referred to as the first-order dispersion approximation. Under these conditions, the group delay of the dispersive medium, defined as $\tau_g = d\Phi(\omega)/d\omega = \phi_1 + \phi_2(\omega - \omega_0)$, exhibits a linear variation as a function of frequency. The characteristic first-order dispersion of the medium is determined by the slope of the group delay as a function of ω , ϕ_2 , referred to as the first-order dispersion coefficient. As described above, the first-order dispersion coefficient is then related to the GVD parameter β_2 through $\phi_2 = \beta_2 \times z$, where we recall again that z is the propagation distance through the dispersive medium.

To complete the description of pulse propagation through a first-order dispersive medium, we recall here a widely used equivalent mathematical model. The propagation of a pulse with complex amplitude $A(t, z = 0)$, centered at a carrier frequency ω_0 , along a first-order dispersive medium is described by the following equation [58]:

$$\frac{\partial A}{\partial z} = \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} \quad (1.6)$$

where the variable t herein is described in a frame that is moving at the medium's group velocity. Said other way, Eq. (1.6) ignores the group delay ($\beta_1 \times z$) through the system, as this simply represents an overall delay of the propagating (dispersed) pulse. Interestingly, Equation (1.6) is mathematically equivalent to the paraxial wave equation that governs the diffraction of continuous wave (CW) light [1] and in particular, it becomes identical to that equation when diffraction occurs in only one transverse direction and β_2 is replaced by $-\lambda/(2\pi)$, where λ is the wavelength of light. This is the basis of the space-time duality theory, which enables establishing formal analogies between spatial and time-domain effects and processes [60]. Equation (1.6) is readily solved by using the Fourier-transform method with the slowly varying envelope approximation, which assumes that the amplitude $A(z, t)$ varies slowly with z on the scale of an optical cycle. If $\tilde{A}(z, \omega)$ is the Fourier transform of $A(z, t)$ such that

$$A(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{A}(z, \omega) \exp(i\omega t) d\omega \quad (1.7)$$

the solution of Eq. (1.6) is given by

$$\tilde{A}(z, \omega) = \tilde{A}(0, \omega) \exp\left(\frac{i}{2} \beta_2 \omega^2 z\right) \quad (1.8)$$

Equation (1.8) shows that GVD changes the phase of each spectral component of the pulse by an amount that depends on the frequency and the propagated distance. From Eq. (1.8), we can define the linear spectral transfer function of the first-order dispersive medium, as follows:

$$H(\omega) \propto \exp(j\Phi(\omega)) = \exp\left(j \frac{\beta_2 \omega^2 z}{2}\right) = \exp\left(j \frac{\phi_2 \omega^2}{2}\right) \quad (1.9)$$

This is the transfer function that was defined above to model a first-order dispersive medium, simply ignoring the linear term of $\Phi(\omega)$, β_1 . We recall again that this term represents a temporal delay and does not affect the pulse shape, so it can be neglected for the discussions at hand, without loss of generality. To summarize, a first-order dispersive medium can be described through a linear spectral transfer function that exhibits a constant amplitude response and a quadratic spectral phase in the frequency domain. Examples of widely used dispersion media in

the context of optical communications and related applications include optical fibers, linearly chirped fiber Bragg gratings (LC-FBGs), prisms and diffraction gratings [1, 14, 61].

1.4.2 Dispersion-induced temporal self-imaging (TSI) or temporal Talbot effect

The temporal Talbot effect refers to the creation of self-images of a periodic waveform (e.g., pulse) train as this propagates through a first-order dispersive medium under well-established specific conditions. The temporal Talbot effect is the time domain counterpart of the spatial Talbot effect; as mentioned, the effect is observed when a periodic train of optical waveforms (e.g., pulses), with repetition period T , propagates through a dispersive medium (DM) under the first-order dispersion approximation. As can be observed in Figure 1.8, as the periodic temporal pulses propagate through the dispersive medium, such as an optical fiber, they start to broaden until their wings overlap (not shown in the figure, for clarity). The propagated pulses at this point are typically of no use because the pulses do not retain their individuality, a process that adversely affects information transfer. However, as the propagation continues on, the broadened pulses in the pulse train begin to interfere with adjacent pulses and under a specific condition, i.e., at the so-called Talbot distances, the original input pulse train will be exactly replicated. This is the *integer* temporal self-imaging effect. In addition to this effect, at some fractional distances, the original pulse train re-emerges but with a multiplied repetition rate, that is with a repetition rate that is an integer multiple of the original one. This is the *fractional* temporal self-imaging effect.

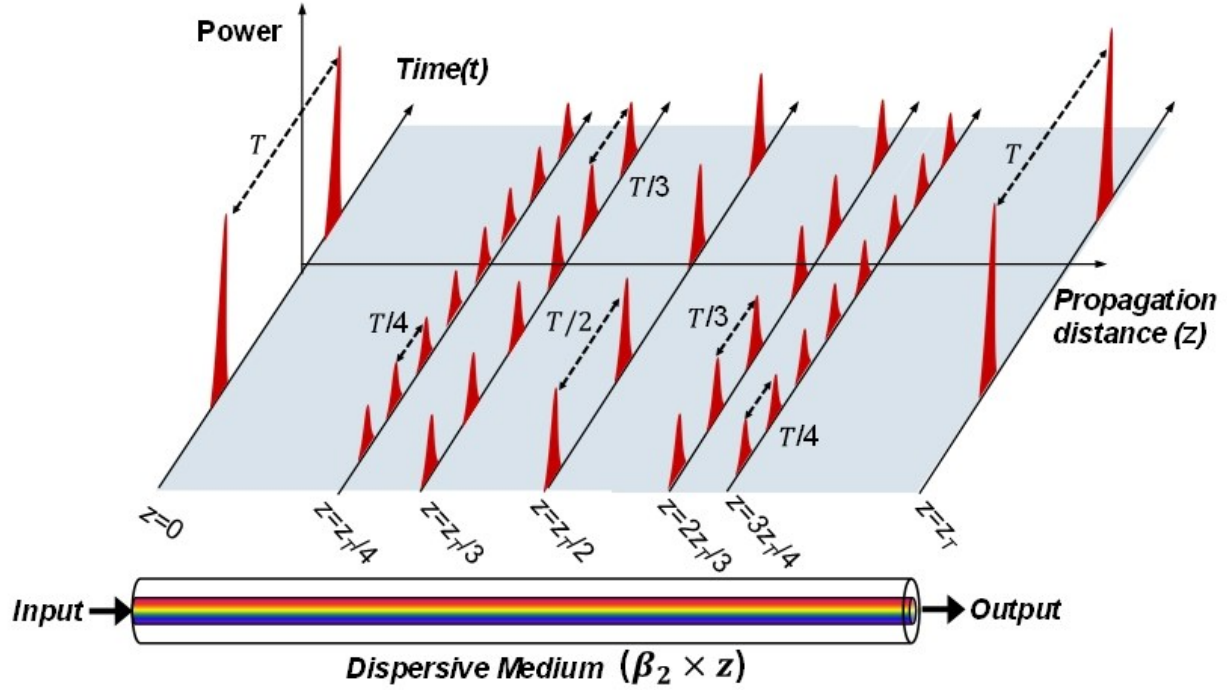


Figure 1.8-Temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium.

Figure 1.8 represents the evolution of a repetitive input pulse train through propagation along a first-order dispersive medium; consistently with the descriptions above, a piece of optical fiber is assumed, where the slope of group delay linearly increases with the propagation distance z , i.e., $\phi_2 = \beta_2 \times z$. For a more formal mathematical description, let us assume that the complex envelope of the input periodic signal $A_{in}(t)$, shown in Figure 1.8 at $z = 0$ (where z represents the axial propagation coordinate), can be expressed as

$$A_{in}(t) = A(t, z = 0) = \sum_{p=-\infty}^{\infty} a_0(t - pT) \quad (1.10)$$

where T is the repetition period and $a_0(t)$ is an arbitrary temporal shape within each period in the interval $|t| \leq T/2$, and $a_0(t) = 0$, for $|t| > T/2$. The corresponding average optical power for this input pulse train can be defined as $P_{in}(t) = |A_{in}(t)|^2$.

As mentioned above, linear propagation through a dispersive medium under the first-order dispersion approximation can be expressed by the spectral transfer function in Eq. (1.9). By using a signal-theory-based approach for all cases of Talbot effect (integer and fractional Talbot effects) [1], the complex envelope spectrum $\tilde{A}_{out}(\omega)$ of the output pulse $A_{out}(t)$ can be obtained

by directly multiplying the spectrum of the input complex envelope $\tilde{A}_{in}(\omega) = F\{A_{in}(t)\}$ and the spectral transfer function $H(\omega)$ in Eq. (1.9):

$$\tilde{A}_{out}(\omega) = \tilde{A}_{in}(\omega) \times H(\omega) \quad (1.11)$$

Recall that under the first-order dispersion approximation, the dispersion value linearly increases with the propagation distance z ($\phi_2 = \beta_2 \times z$). Therefore, for different propagation distances within z , we can observe various forms of the output signal. For example, in fig.1.8, the input pulse train at distance $z=0$ is exactly self-imaged after propagation along a dispersive medium at a distance $z = s \times z_T$, where z_T is the basic integer Talbot distance defined as

$$z_T = \frac{T^2}{2\pi\beta_2} \quad (1.12)$$

and with $s=1, 2, 3 \dots$ etc.

For even values of s ($=2, 4, 6, \dots$), the output signal is an exact replica of the input signal. For odd values of s ($=1, 3, 5, \dots$), the original signal is also reproduced but with half-period shift $T/2$. In summary, at fiber distances which are at an integer multiple of the basic Talbot distance $z_T = T^2/2\pi\beta_2$, exact replicas of the input signal are reproduced either with an exact synchronization with respect to the input pulse train (direct integer Talbot effect) or with an additional delay by exactly half of the original period (inverted integer Talbot effect). In addition to the described reconstruction images, one finds other interesting patterns. In particular, at fractional distances of:

$$z = \frac{s}{m} z_T = \frac{s}{m} \frac{T^2}{2\pi\beta_2} \quad (1.13)$$

with $s = 1, 2, 3, \dots$, $m = 2, 3, 4, \dots$, such that (s/m) is a noninteger and irreducible rational number, the output signal is a copy of the periodic input signal (where each individual pulse maintains its shape and temporal width), but with a repetition-rate m times that of the input signal. In this case, the individual output pulse power is reduced correspondingly by the factor of m , ignoring potential insertion losses of the dispersive medium. Figure 1.8 shows examples of output pulse trains at the fractional Talbot distances $z = z_T/4$, $z_T/3$, and $z_T/2$ where the input repetition-rate has been multiplied by factors of $m = 4, 3$ and 2 , respectively. This repetition rate multiplication process only changes the repetition-rate of the signal's intensity, while the spectrum magnitude of the signal remains unchanged. This translates into a deterministic pulse-to-pulse residual temporal phase on the output pulse train. This residual temporal phase

indicates the case where the waveform field amplitude is advanced or delayed with respect to the envelope centre. This feature will be discussed in further detail later below in this section. It should also be mentioned that the maximum repetition rate at the output is limited to the input pulse width. The input pulse width must be short enough so that the pulses do not overlap on the multiplied output train; in particular, assuming that the Talbot condition is satisfied, then $m \leq D_{out_max} T / t_{in}$ where t_{in} is the input pulse width and D_{out_max} is the maximum duty cycle of output pulses before pulse-overlapping occurs [62].

In order to present a more intuitive way into the principle of the temporal Talbot effect, we can use joint time-frequency (TF) representations of the involved signals, as shown in Figure 1.9. For each TF representation, the bottom axis represents the temporal variation of the pulse train and the left axis represents the corresponding spectrum, with the 2D energy distribution shown in the larger central plot. Figure 1.9(a) shows an example when the integer Talbot effect is considered (i.e., $m=1$). In this case, the dispersive medium, with coefficient of $\phi_2 = \beta_2 \times z = T^2/2\pi$ introduces a group delay ($\Delta\tau_g = \phi_2\Delta\omega$) of T between two adjacent discrete frequency components with frequency spacing of $F (= 1/T)$, i.e., $\Delta\omega = 2\pi/T$. Thus, the spectral components of the input pulse train are tilted to different temporal positions by the group delay of the dispersion medium and are again distributed by the input pulse period of T . Spectral superimposition of the resultant dispersed pulse train produces an exact self-image of the original pulse train at the fiber output, as illustrated in Figure 1.9(a).

Figure 1.9(b) shows the case when the input signal is a periodic pulse train and we target a repetition rate division factor of two (Eq. (1.13) with $s=1$, $m = 2$). The dispersion coefficient is set to $\phi_2/2 = \beta_2 \times z/2 = T^2/4\pi$ and introduces a group delay of $T/2$ between two adjacent discrete frequency components with original frequency spacing of $F (=1/T)$. Similar to the previous mechanism, each spectral components are tilted to different temporal positions and redistributed into the new temporal positions between adjacent frequency components, leading to the predicted creation of new pulses with a temporal period of $T/2$, as shown in figure 1.6(b).

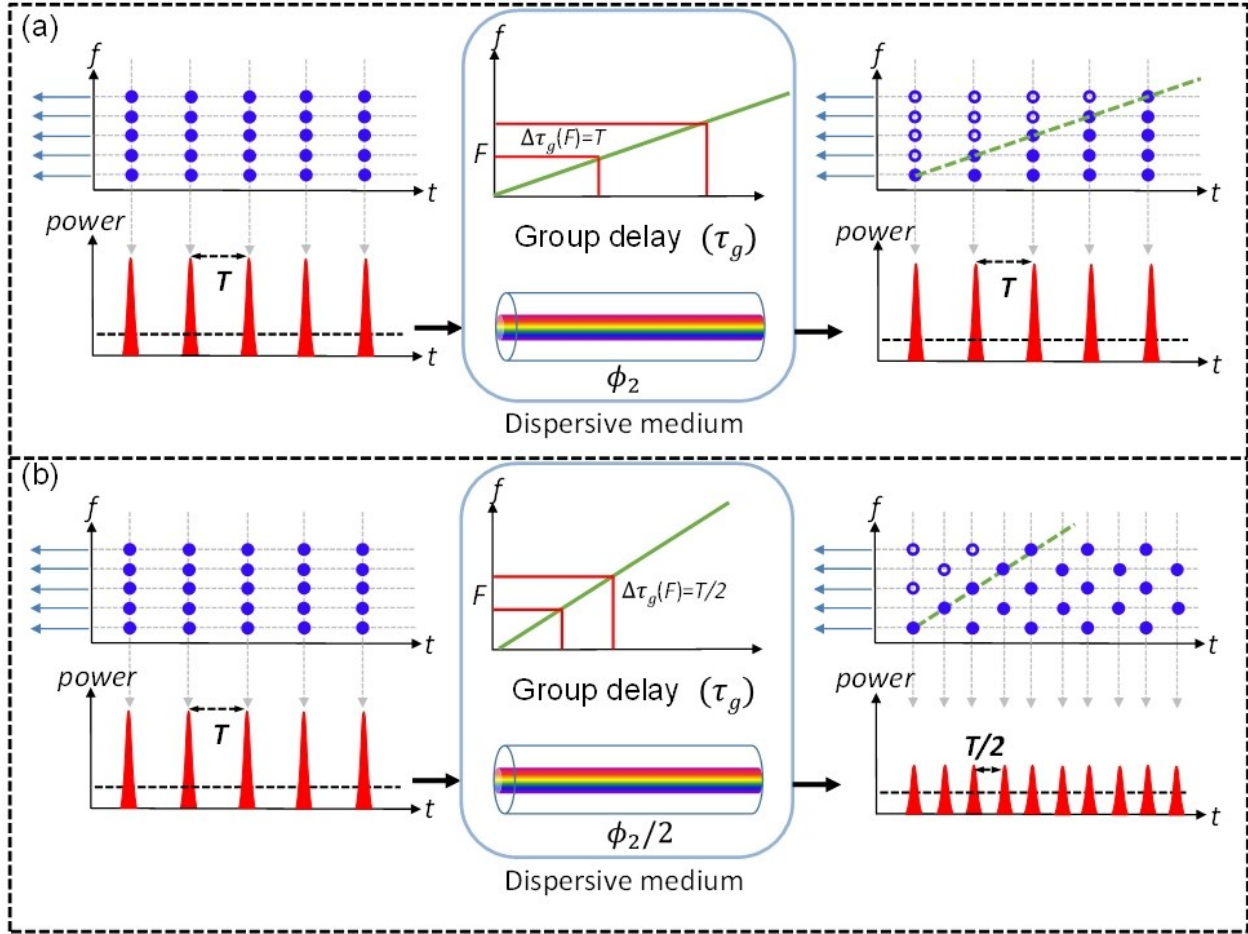


Figure 1.9-Joint time-frequency analysis of the temporal Talbot effect. t : time, f : frequency.

So far, our discussions have focused on the temporal intensity distributions of the pulse trains that are produced by temporal Talbot effect; however, there is another important feature to be discussed in what follows. As mentioned above, the rate-multiplied pulse trains that are produced by the fractional Talbot effect exhibit deterministic pulse-to-pulse residual temporal phase variations. These phase variations provide a powerful tool for control and manipulation of the output pulse trains that can be produced by Talbot effect.

As shown in Figure 1.10, in an integer Talbot self-image, the uniform phase profile of the input is restored, as can be seen e.g., in the self-imaged pulses at a distance z_T in the carpet. Notice that in this illustration, the temporal phase profiles of the resulting pulse trains are represented by the dashed blue lines. However, the rate-multiplied self-images are affected by a deterministic pulse-to-pulse residual phase, such as those observed at $z_T/3$ and $z_T/2$. The residual phase for a particular fractional image can be analytically calculated for a given s and m [63].

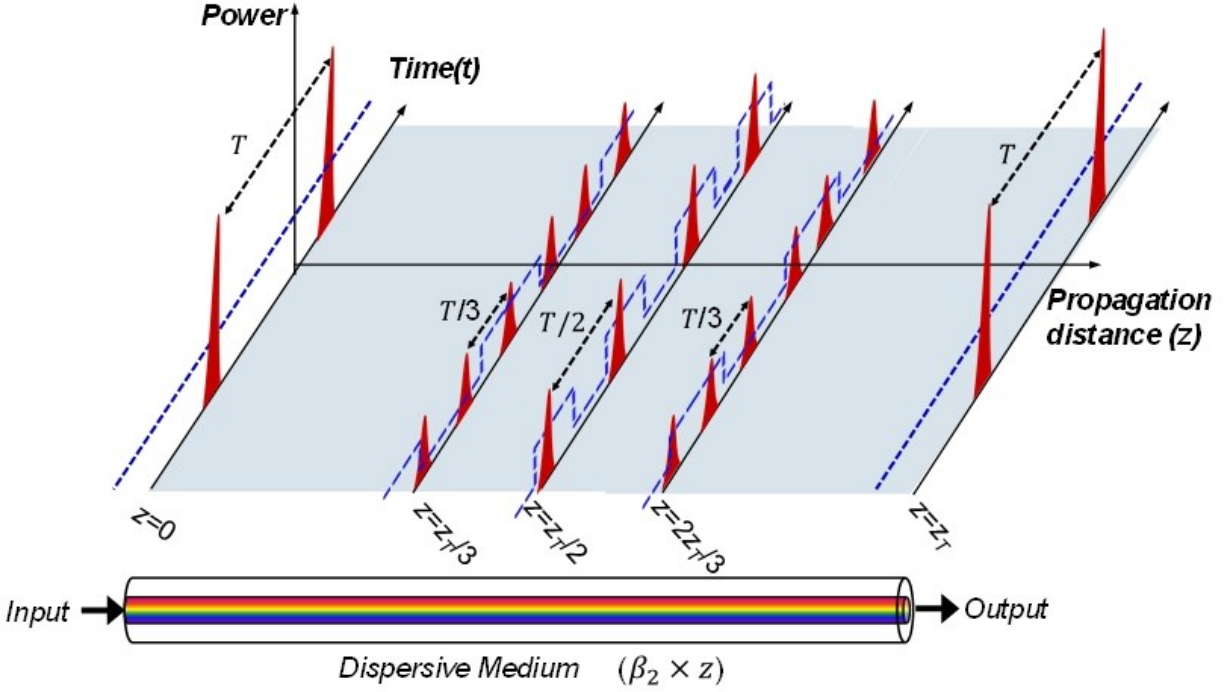


Figure 1.10-Temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium and the residual temporal phase variations of the resulting temporal pulse trains (represented by the dashed blue lines).

In particular, the phase function of the n -th pulse of a particular fractional image, for a given s and m , is defined by the following equation [63]:

$$\varphi_n = -\frac{s}{m} \left(\begin{bmatrix} 1 \\ s \end{bmatrix}_m \right)^2 \pi n^2 \quad (1.14)$$

when $s \cdot m$ is even and

$$\varphi_n = -2(s/m) \left[\frac{1}{2} \right]_m \left(\left[\frac{1}{2s} \right]_m \right)^2 \pi (2n+m)^2 \quad (1.15)$$

when $s \cdot m$ is odd. In these equations, $[1/a]_b$ is the inverse of a modulo b , s is an integer and co-prime with m ($= 2, 3, 4, \dots$) and $n=0, 1, 2, \dots$ is the pulse number. Notice that the discrete phase profiles defined in Eqs. (1.14) and (1.15) are periodic with a fundamental period equal to m , namely $\varphi_n = \varphi_{n+m}$. The temporal phase functions defined in Eq. (1.14) and (1.15) show a quadratic dependence with the pulse position, identified by the factor n . This behavior is actually equivalent to the effect of a continuous temporal quadratic phase modulation and creates m times as many frequency tones in the spectrum of the input signal, with a comb frequency spacing that is reduced by m times with respect to the input. This

is known as the spectral self-imaging effect [64]. If these phase shifts are reduced to a 2π range, a periodic sequence of discrete phase steps in the range $[0, 2\pi]$ is obtained.

1.4.3 Conventional inverse temporal self-imaging (I-TSI)

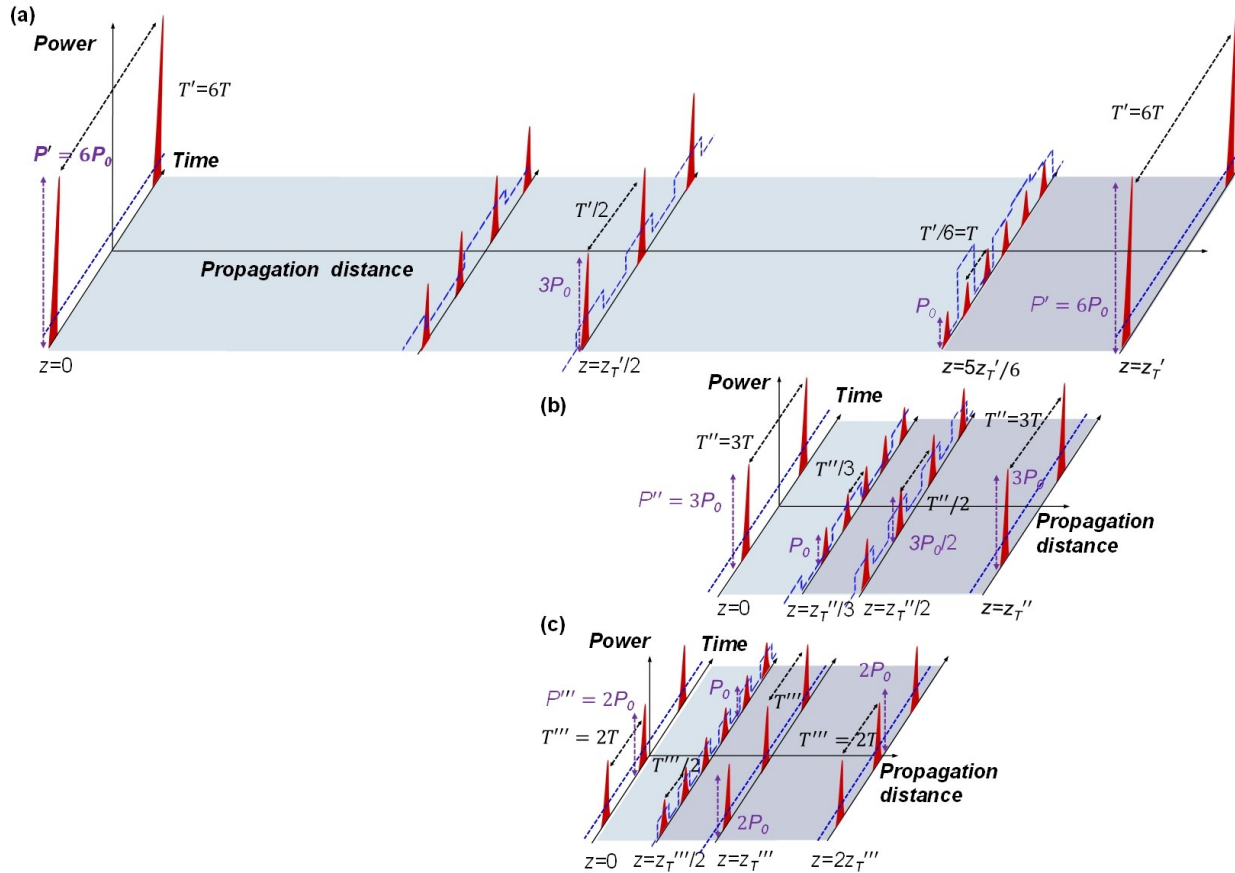


Figure 1.11-The standard temporal Talbot effect. Evolution of a repetitive input pulse train through propagation along a first-order dispersive medium. Talbot carpet when for different repetition periods: (a) $T' = 6T$; (b) $T'' = 3T$; (c) $T''' = 2T$.

The I-TSI is a reverse-engineering of the temporal Talbot effect (TSI effect), in which the final amplified temporal image is recovered from a previous rate-multiplied self-image. As shown in Fig. 1.11, top, in the standard temporal Talbot effect, a flat-phase repetitive input waveform (signal at $z=0$) is self-imaged, after dispersive propagation through a distance z_T' (integer Talbot distances). There also exists an infinite amount of fractional distances, defined by the “Talbot Carpet” [1, 11, 55, 56, 65], where one can observe rate-multiplied self-images of the input waveform train (fractional Talbot effect), with correspondingly reduced individual waveform intensity. The examples in Fig. 1.11(a) at Talbot distances $z_T'/2$ and $5z_T'/6$, have intensities reduced by the factors by which the repetition rate is multiplied, $m=2$ and $m=6$, respectively. In an integer Talbot self-image, the uniform phase profile of the input is restored, as can be seen e.g., in the self-imaged pulses at a distance z_T' in the top carpet (phase profiles

represented by the dashed blue lines). However, the rate-multiplied self-images are affected by a deterministic pulse-to-pulse residual phase, such as those observed at $z_T'/2$ and $5z_T'/6$.

In the original designs of the I-TSI effect, as first proposed for Talbot amplification [18], illustrated in Fig. 1.12, it was proposed to precondition an input pulse train to mimic the repetition rate and temporal phase of rate-multiplied self-images, e.g., at $z_T'/2$ and $5z_T'/6$ in the specific example shown in Fig. 1.12. By propagating these pulse trains to the nearest self-image distance z_T' , the pulse train intensity is amplified by the amount of repetition rate reduction. In the cases where preconditioned inputs are made to match the pulse train at $z_T'/2$ and $5z_T'/6$, amplification factors of the output train are $m=2$ and $m=6$, respectively (the case for amplification by $m = 6$ is shown in Fig. 1.12). Following this design strategy, the dispersive medium must introduce a total dispersion value that increases linearly with the repetition rate division, or pulse amplification, factor m , in particular [18]

$$\phi_2 = \beta_2 z = m \frac{T^2}{2\pi} \quad (1.16)$$

where I recall that m is the amplification factor or rate-division factor, T is the repetition period of the input pulse train, z is the length of the dispersive medium and β_2 is the dispersion coefficient, defined as the slope of the group delay as a function of the radial frequency ω , per unit length. The operation principles of the works reported in refs. [3, 18] are based on the concept of inverse-temporal self-imaging (I-TSI), involving a combination of phase modulation and dispersion, as first introduced in ref. [18] and illustrated in Fig.1.12. Previous work on Talbot amplification by I-TSI [18] has successfully shown an experimental demonstration of passive amplification, with gain factors of $m=2$, 5, 15, and 27 at the output of a dispersive fiber link implemented with a single-mode optical fiber. In particular, a total dispersion of $\sim 2,650$ ps/nm was used for the case of $m=2$ and $m=5$ (by modifying the repetition rate of the input pulse train to match the needed Talbot conditions) and of $\sim 8,000$ ps/nm for $m=15$ and $m=27$ (again, by modifying the input pulse rate to match the corresponding Talbot conditions). In addition, the I-TSI effect on aperiodic pulse trains has been also demonstrated and investigated [3]. In this previous work, authors have reported successful clock extraction of 4.85-GHz, 3.23-GHz, and 2.43-GHz sub-harmonic clock signals, as well as the 9.7-GHz base-rate clock, from a 2^7-1 PRBS 9.7-Gbit/s RZ-OOK data signal. The corresponding dispersion values used for demonstration are ~ 2647 ps/nm, ~ 3972 ps/nm, and ~ 5294 ps/nm for SH-CR orders of $m = 2, 3$ and 4 , respectively. Thus, as per the original I-TSI designs [3, 18], each amplification factor or rate division factor requires a new dispersion value, typically implemented by physically changing the dispersive element (spool of fiber, fiber Bragg grating, etc.).

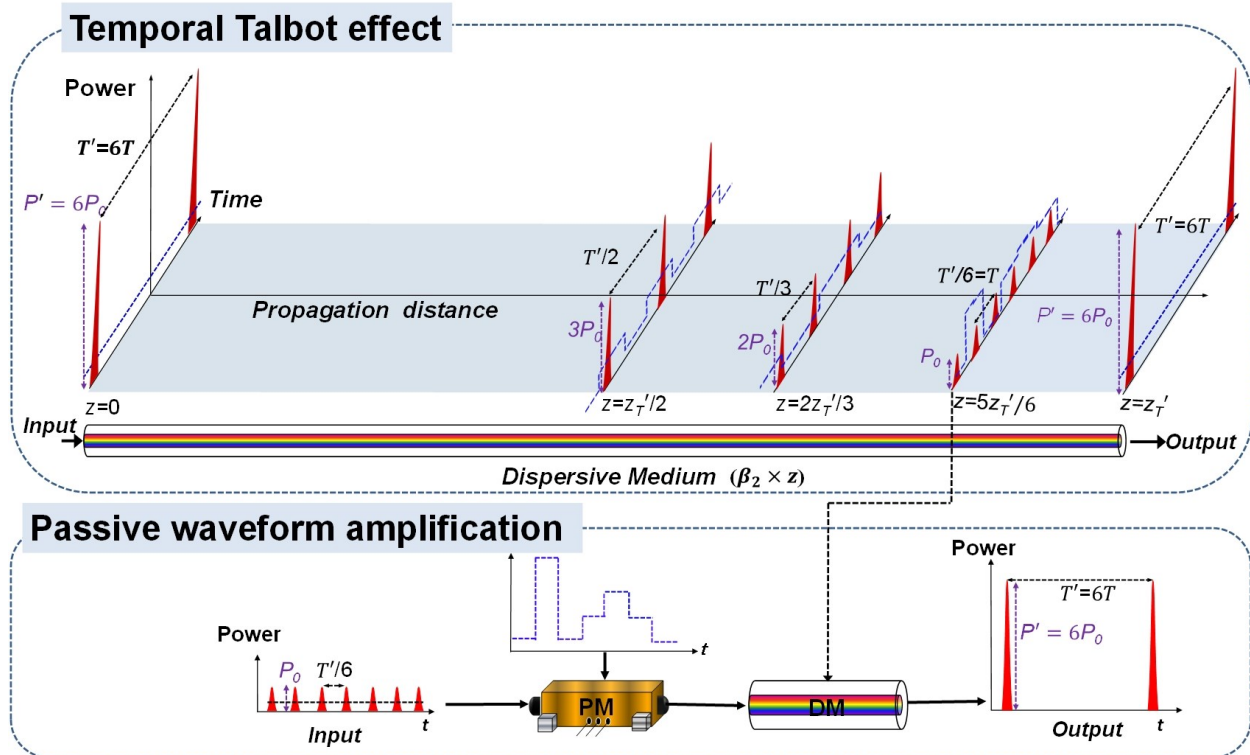


Figure 1.12-The original design for the conventional Talbot amplifier. Coherent addition of repetitive pulse waveforms is achieved by tailoring the temporal phase of the input waveform train and subsequent propagation through a dispersive medium such that the individual waveform intensity (energy) is amplified by an amount the repetition rate is reduced. Adapted from Ref. [18].

1.4.4 Generalized design for I-TSI

The central contribution of this Thesis is a new, generalized set of design equations for inducing the I-TSI effect. This innovative design strategy enables tuning of the repetition rate-division, or pulse amplification, factor by simply changing the temporal phase modulation profile, without modifying the dispersion amount. For this purpose, we introduce a non-trivial generalization of the dispersion equations that allow one to induce a desired I-TSI effect (i.e., design equations for the phase modulation and dispersive stages), leading to a relatively wide range of different rate-division factors, i.e., pulse amplification factors, for a fixed, prescribed dispersion, by suitably programming the temporal phase modulation step. The generalized design strategy at the core of this work is described in greater detail in Chapter 2. A summary of this strategy is presented here in what follows.

Figure 1.11 shows the concept of achieving programmable amplification factors or rate-division factors using the same dispersive delay. The idea can be understood through a comparison of the three different Talbot carpets shown in Fig. 1.11(a), Fig. 1.11(b), and Fig. 1.11(c), each corresponding to a

different input repetition period, $T' = 6T$, $T'' = 3T$, and $T''' = 2T$. All carpets show the same repetition rate, T , at the fractional Talbot distances $5z_T'/6$, $z_T''/3$, and $z_T'''/2$, respectively. If we precondition an input pulse train to match the waveforms at these fractional distances (same period, T , but different residual temporal phases), propagation through the same amount of dispersive delay (shown with purple shading in the plots) will result in a flat-phase output pulse train with amplification factors $m=6$, $m=3$, and $m=2$, respectively. In this example, the same dispersive propagation distance required for both amplification factors is $z_T'/6 = 2z_T''/3 = 3z_T'''/2 = T'/(12\pi\beta_2)$. The key to this proposed design is that in order to ensure the same propagation length in the three cases, we select the first integer Talbot plane ($q=0$, where q is a free-design parameter to number the used integer plane) in the top carpet, and the first integer Talbot plane ($q=0$) in the middle carpet as well, but the third integer Talbot plane ($q=1$) in the bottom carpet.

This example provides the needed guidelines to obtain the generalized equations based on I-TSI effect for repetition-rate division (and pulse amplification) of an input waveform train, with a repetition period equal to T , by a rate-division (amplification gain) factor of m ($=2, 3, 4, \dots$). For these derivations, we assume the general input plane location in the Talbot carpet to be at $(s/m)z_T$, where z_T is the fundamental integer Talbot distance corresponding to an input period equal to m times the period T , ($T_0 = m \times T$), and we recall that s is an integer and co-prime with m . Similarly, the general output plane location is at $(q+1)z_T$, with $q=0, 1, 2, \dots$. The input waveform train should be first phase modulated according to the Talbot phase modulation function corresponding to the input location $(s/m)z_T$ in the carpet, by using Eq. (1.14) and (1.15) [64]. Subsequently, the modulated pulse train should propagate through the following amount of dispersion:

$$\phi_2 = (qm + m - s)mT^2/2\pi \quad (1.17)$$

At this point, it is worth mentioning that setting $s=m-1$ and $q=0$ (first integer Talbot plane) in the generalized equations in Eq. (1.17) and Eq. (1.14, 1.15) gives rise to the conventional dispersion equation, $\phi_2 = mT^2/2\pi$, Eq. (1.16), and application of the temporal phase-modulation profile ($\phi_n = (m - 1/m)\pi n^2$) previously defined for conventional I-TSI based Talbot amplification, as reported in [18].

Getting back to our generalized design strategy, let us now consider the situation where we choose a maximum gain factor $m=M$. The corresponding required dispersion value by setting $q=0$ and $s=M-1$ is $\phi_2=MT^2/2\pi$. Indeed, for a prescribed input temporal period T , we can now use this same dispersion value for a wider range of gain factors, satisfying $\phi_2=(qm+m-s)mT^2/2\pi=MT^2/2\pi$, according to Eq. (1.17)

above. In this equation, s and q are free design parameters, and as such, we can obtain a number of different gain factors m , being smaller or equal to M ($m \leq M$), that satisfy this condition for a given s and q . The required phase modulation functions can be then obtained using Eq. (1.14) and (1.15) with the corresponding m and s factors. In a practical setup for processing optical waveform trains, the temporal phase modulation process can be implemented using an electro-optic modulation process, where the optical signal is modulated by an electronic waveform. The latest can be generated from an electronic arbitrary waveform generator (AWG), which can be easily programmed to produce the desired target modulation profile. This is the basis for the electronic programmable designs proposed in my Master thesis for (i) passive amplification of repetitive optical waveforms and (ii) sub-harmonic clock recovery from RZ-OOK telecommunication data signals, based on I-TSI.

1.4.5 Considerations on practical implementations of I-TSI

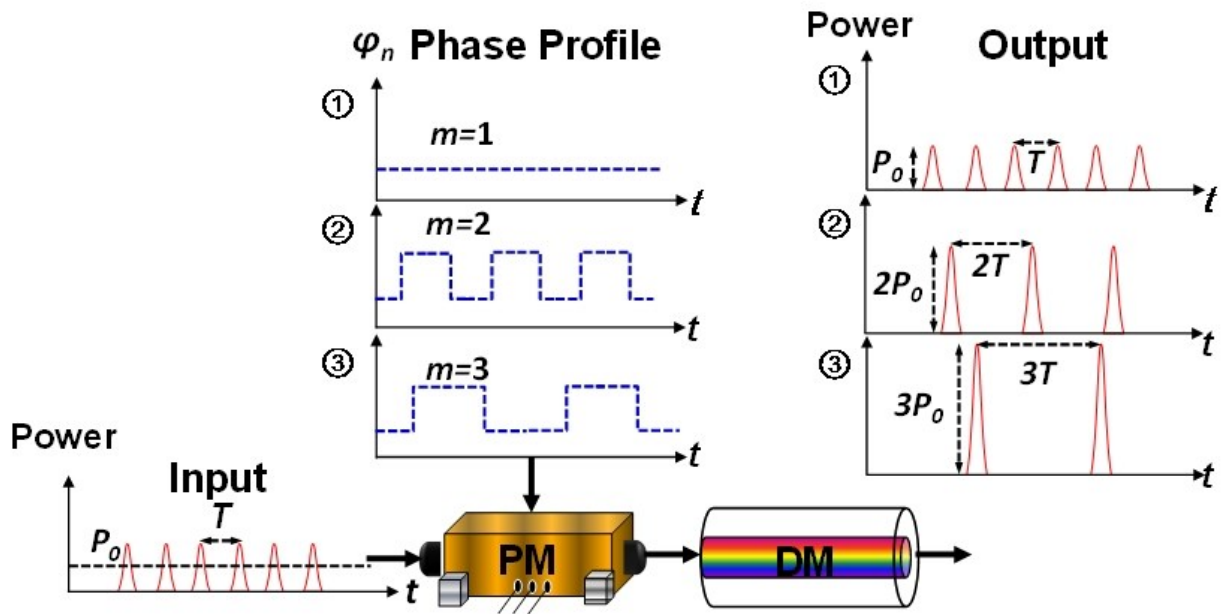


Fig. 1.13- Programmable method for phase preconditioning pulse trains for dispersion-induced I-TSI effect. PM: phase modulator. DM: dispersive medium.

Recall that the I-TSI is a reverse-engineering of the TSI effect, in which the final amplified temporal image is recovered from a previous rate-multiplied self-image. The I-TSI effect on optical waveforms can be implemented using a combination of electro-optics phase modulation and a fiber-optics dispersive medium, e.g., as shown in Fig. 1.13. In my work, the dispersive medium has been implemented using a LC-FBG operating in reflection [1]. This is created by photo-inscribing a periodic perturbation of the refractive index along the core of a single-mode fiber so that the period of the perturbation is linearly

chirped along the device length. This translates into different frequencies (Bragg frequencies) being reflected at different positions along the grating device, with the reflected frequency changing linearly along the device length, leading to a group delay curve that depends linearly on the frequency variable. As such, similarly to any nearly first-order dispersive device, a reflective LC-FBG can be described through a linear spectral transfer function that exhibits a constant amplitude response and a quadratic spectral phase in the frequency domain. An LC-FBG can be designed to provide a very large amount of dispersion, i.e., equivalent to the dispersion provided by hundreds of kilometers of a conventional single-mode optical fiber, over a very broad bandwidth (easily of a few THz, sufficient to cover the bandwidth of picosecond-resolution temporal waveforms), and in a very compact format, with a length as short as a few tens of centimeters. An LC-FBG must be operated in reflection so it needs to be incorporated into an additional device (e.g., circulator) to retrieve the reflected signals. A well-known drawback of a LC-FBG is that it may exhibit group-delay ripples that may affect propagation of a broadband pulse. In order to minimize the effect of group delay ripples in the LC-FBG used in our experiments, the input pulse bandwidth was reduced to ~ 0.200 nm (25 GHz) with a Gaussian-like band-pass filter, thereby increasing the input pulse width entering into the Talbot amplifier to ~ 17 ps (intensity full-width at half maximum, FWHM).

Before spectral phase filtering from dispersive propagation, a suitable temporal phase is added through an electro-optic phase modulator. Recall that this is a device that enables modulating the temporal phase of an incoming optical wave according to the electrical voltage profile applied on an electro-optic crystal [66]. For an optimal modulation performance, the polarization of the electric field of the input optical wave needs to be properly set to match the properties of the electro-optic crystal. Currently, electro-optic phase modulators for modulation of optical signals at speeds approaching 100 GHz are commercially available [67]. The output optical waveform intensity will be locally amplified according to the amount of repetition rate reduction that is induced by the temporal phase modulation profile. In our work, the appropriate multilevel temporal phase modulation required for a desired amplification factor was applied to the optical pulses using a commercial fiber-integrated electro-optic phase modulator (40 GHz bandwidth) driven by an electronic AWG (Tektronix AWG7122C, 7.5 GHz analogue bandwidth). Though the prescribed phase drive shows the same phase values over entire pulse bit-slots, we note that this technique only requires the correct constant phase over the pulse width, providing a high-tolerance to errors in the phase drive. This allowed us to use a 7.5-GHz AWG to effectively manipulate a 19.2-GHz signal, pulse-by-pulse.

As mentioned before, the operation principles of the works reported in refs. [3,18] and our present work are all based on the concept of I-TSI effect, involving a combination of phase modulation and dispersion, as first introduced in ref. [18]. However, in previous designs, a different gain factor necessarily requires

the use of a different amount of dispersion (i.e., physically changing the dispersive medium), so that the system is set for waveform amplification by a fixed, prescribed gain factor or rate division factor, and it cannot be easily tuned afterwards. In our work, through the introduction of a non-trivial generalization of the equations based on I-TSI (i.e., design equations for the phase modulation and dispersive stages), we are able to obtain a relatively wide range of different gain factors or rate division factor using a fixed dispersion, which can be electrically reconfigurable by suitably programming the temporal phase modulation step in an electro-optic modulator device. The needed temporal phase modulation profiles can be pre-calculated by the newly founded generalized equation for I-TSI in Eq. (1.17). Programmability can be achieved by using a fixed fiber-optics dispersive line (or a linearly chirped fiber-Bragg grating), through electronic reconfiguration of the driving voltage in the electro-optic modulator.

1.5 References and links

- [1] J. Azaña and M. A. Muriel, "Temporal self-imaging effects: theory and application for multiplying pulse repetition rates," *IEEE J. Sel. Top. Quantum Electron.* 7(4), 728–744 (2001).
- [2] J. Azaña and M. A. Muriel, "Temporal Talbot effect in fiber gratings and its applications," *Appl. Opt.* 38(32), 6700–6704 (1999).
- [3] R. Maram, L. R. Cortes, and J. Azaña, "Sub-harmonic periodic pulse train recovery from aperiodic optical pulse sequences through dispersion-induced temporal self-imaging," *Opt. Exp.* 23(3), 3603-3613 (2015.)
- [4] J. Azaña and L. R. Chen, "General temporal self-imaging phenomena," *J. Opt. Soc. Am. B* 20(7), 1447-1458 (2003).
- [5] J. Caraquitena, Z. Jiang, D. E. Leaird, and A. M. Weiner, "Tunable pulse repetition-rate multiplication using phase-only line-by-line pulse shaping," *Opt. Lett.* 32(6), 716–718 (2007).
- [6] D. Pudo and L. R. Chen, "Tunable passive all-optical pulse repetition rate multiplier using fiber Bragg gratings," *J. Lightwave Technol.* 23(4), 1729–1733 (2005).
- [7] J. H. Lee, Y. M. Chang, Y. G. Han, S. H. Kim, and S. B. Lee, "2 ~ 5 times tunable repetition-rate multiplication of a 10 GHz pulse source using a linearly tunable, chirped fiber Bragg grating," *Opt. Express* 12(17), 3900–3905 (2004).
- [8] C. J. S. de Matos and J. R. Taylor, "Tunable repetition-rate multiplication of a 10 GHz pulse train using linear and nonlinear fiber propagation," *Appl. Phys. Lett.* 83(26), 5356–5358 (2003).

- [9] J. Caraquitená and J. Martí, "High-rate pulse-train generation by phase-only filtering of an electrooptic frequency comb: analysis and optimization," *Opt. Commun.* 282(18), 3686–3692 (2009).
- [10] R. Maram, L. R. Cortes, and J. Azaña, "Programmable fiber-optics pulse repetition-rate multiplier," *J. Lightwave Technol.* 34(2), 448-455 (2016).
- [11] F. Mitschke and U. Morgner, "The temporal Talbot effect," *Opt. Photon. News* 9, 45–47 (1998).
- [12] S. Arahira, S. Kutsuzawa, Y. Matsui, D. Kunimatsu, and Y. Ogawa, "Repetition-frequency multiplication of mode-locked pulses using fiber dispersion," *J. Lightwave Technol.*, 16(3), pp. 405–409 (1998).
- [13] I. Shake, H. Takara, S. Kawanishi, and M. Saruwatari, "High-repetition-rate optical pulse generation by using chirped optical pulses," *Electron. Lett.*, 34(8), pp. 792–793, 1998.
- [14] S. Longhi, M. Marano, P. Laporta, O. Svelto, M. Belmonte, B. Agogliati, L. Arcangeli, V. Pruneri, M. N. Zervas and M. Ibsen, "40-GHz pulse train generation at 1.5 m with a chirped fiber grating as a frequency multiplier," *Opt. Lett.* 25, 1481–1483 (2000).
- [15] J. Azaña and M. A. Muriel, "Technique for multiplying the repetition rates of periodic trains of pulses by means of a temporal self-imaging effect in chirped fiber gratings," *Opt. Lett.*, 24(23), pp. 1672–1674 (1999).
- [16] D. Pudo, M. Depa, and L. R. Chen, "Single and multiwavelength all-optical clock recovery in single-mode fiber using the temporal Talbot effect," *J. Lightwave Technol.* 25(10), 2898–2903 (2007).
- [17] D. Pudo, M. Depa, and L. R. Chen, "All-optical clock recovery using the temporal Talbot effect," in *Proceedings of Optical Fiber Communication (OFC) Conference, Anaheim, USA*, paper: OThB7 (2007).
- [18] R. Maram, J. Van Howe, M. Li, and J. Azaña, "Noiseless intensity amplification of repetitive signals by coherent addition using the temporal Talbot effect," *Nat. Commun.* 5, 5163 (2014), doi:10.1038/ncomms6163.
- [19] R. Maram, L.R. Cortés, J. Van Howe, J. Azaña, "Energy-preserving arbitrary repetition-rate control of periodic pulse trains using temporal Talbot effects," *IEEE/OSA J. Lightwave Technol.*, 35, pp. 658-668 (2017).
- [20] R. Maram, M. Seghilani, J. Jeon, X-Z. Li, L. Romero Cortés, J. van Howe, and J. Azaña, "Demonstration of input-to-output gain and temporal noise mitigation in a Talbot amplifier," *Photon. Technol. Lett.* 30(8), 665-668 Feb. (2018).

- [21] Helmchen, F. & Denk, W., "Deep tissue two-photon microscopy," *Nat. Methods* 2, 932 (2005).
- [22] J. Cheng, C.-Liu, S. Shang, D. Liu, W. Perrie, G. Dearden, and K. Watkins, "A review of ultrafast laser materials micromachining," *Opt. Laser Technol.* 46, 88–102 (2013).
- [23] Desurvire, Emmanuel, "Erbium-doped fiber amplifiers: principles and applications," Wiley-Interscience (2002).
- [24] M. J. Connelly, "Semiconductor optical amplifiers," Springer Science & Business Media (2007).
- [25] Kidorf, Howard, et al., "Pump interactions in a 100-nm bandwidth Raman amplifier," *IEEE Photon. Technol. Lett.* 11(5), 530-532 (1999).
- [26] De Forest, L., "The audion-detector and amplifier," *Proc. IEEE* 2(1), 15–29(1914).
- [27] Bardeen, J. & Brattain, W. H., "The transistor, a semi-conductor triode," *Phys. Rev. Lett.* 74, 230–231 (1948).
- [28] Mears, R. J., Reekie, L., Jauncey, M. & Payne, D. N., "Low-noise erbium-doped fiber amplifier operating at 1.54 μm ," *Electron Lett.* 26, 1026–1028 (1987).
- [29] Kozuma, M. et al., "Phase-coherent amplification of matter waves," *Science* 286, 2309–2312 (1999).
- [30] Joachim, C., Gimzewski, J. K. & Aviram, A., "Electronics using hybrid-molecular and mono-molecular devices," *Nature* 408, 541–548 (2000).
- [31] Foster, M. A. et al., "Broad-band optical parametric gain on a silicon photonic chip," *Nature* 441, 960–963 (2006).
- [32] Beardsley, R. P., Akimov, A. V., Henini, M. & Kent, A. J., "Coherent terahertz sound amplification and spectral line narrowing in a Stark ladder superlattice," *Phys. Rev. Lett.* 104, 085501 (2010).
- [33] Tong, Z. et al., "Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers," *Nat. Photon.* 5, 430–436 (2011).
- [34] M. J. Connelly, "Semiconductor Optical Amplifiers", Springer, Verlag (2002).
- [35] G. P. Agrawal and M. J. Potasek, "Nonlinear pulse distortion in single-mode optical fibers at the zero-dispersion wavelength," *Phys. Rev. A* 33, 1765 (1986).
- [36] Abu-aisheh, A. and Moslehpour, S., "Pre-amp EDFA ASE noise minimization for optical receiver transmission performance optimization," *ELSEVIER Optics and Communications*, 283(12), pp. 2603-2606 (2010).

- [37] T. Alexoudi, G.T. Kanellos, S. Dris, D. Kalavrouziotis, P. Bakopoulos, A. Miliou and N. Pleros, "Deterministic timing jitter and pulse peak power equalization analysis," *IEEE Photon. Journal*, 4(5), (2012).
- [38] Haus, H. A., "The proper definition of noise figure of optical amplifier," *Opt. Amp. And their appl.* (Optical Society of America, 2000).
- [39] Mourou, G. A., Tajima, T. & Bulanov, S. V., "Optics in the relativistic regime," *Rev. Mod.Phys.* 78, 309–371 (2006).
- [40] Eidam, T. et al., "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," *Opt. Exp.* 19(1), 255–260 (2011).
- [41] Tummler, J. et al., "High-repetition-rate chirped-pulse-amplification thin-disk laser system with joule-level pulse energy," *Opt. Lett.* 34(9), 1378–1380 (2009).
- [42] Jones, J. R. & Ye, J. Femtosecond pulse amplification by coherent addition in a passive optical cavity. *Opt. Lett.* 27, 1848–1850 (2002).
- [43] Vidne, Y., Rosenbluh, M. & Hansch, T. W. Pulse picking by phase-coherent additive pulse generation in an external cavity. *Opt. Lett.* 28, pp. 2396–2398 (2003).
- [44] Z. Zhu, M. Funabashi, Z. Pan, L. Paraschis, D. L. Harris, and S. J. B. Yoo, "High-performance optical 3R regeneration for scalable fiber transmission system applications," *J. Lightw. Technol.* 25, 504–511 (2007).
- [45] Houbavlis et al, "All-optical signal processing and applications within the Esprit project DO_ALL," *J. Lightw. Technol.* 23, 781–801 (2005).
- [46] H. Hu, H. C. H. Mulvad, M. Galili, E. Palushani, J. Xu, A. T. Clausen, L. K. Oxenlowe, and P. Jeppesen, "Polarization- insensitive 640Gb/s demultiplexing based on four wave mixing in a polarization-maintaining fibre loop," *J. Lightwave Technol.* 28(12), 1789–1795 (2010).
- [47] A. M. de Melo, S. Randel, and K. Petermann, "Mach–Zehnder interferometer-based high-speed OTDM add–drop multiplexing," *J. Lightwave Technol.* 25(4), 1017–1026 (2007).
- [48] C. Ware, L. K. Oxenløwe, F. Gómez Agis, H. C. H. Mulvad, M. Galili, S. Kurimura, H. Nakajima, J. Ichikawa, D. Erasme, A. T. Clausen, and P. Jeppesen, "320 Gbps to 10 GHz sub-clock recovery using a PPLN-based optoelectronic phase-locked loop," *Opt. Exp.* 16(7), 5007–5012 (2008).
- [49] J. Parra-Cetina, J. Luo, N. Calabretta, S. Latkowski, H. J. S. Dorren, and P. Landais, "Subharmonic all-optical clock recovery of up to 320 Gb/s signal using a quantum dash Fabry–Perot mode-locked laser," *Electron. Lett.* 31(19), 3127–3134 (2013).

- [50] J. J. O'Connor and E. F. Robertson, "William Henry Fox Talbot," MacTutor History of Mathematics, (2005). [Online]. Available: <http://www-groups.dcs.st and.ac.uk/history/Biographies/Talbot.html>. [Accessed 10 05 2016].
- [51] A. Winkelmann, "Übereinige Erscheinungen, die bei der Beugung des Lichtes durch Gitter Auftreten," *Ann. Phys. (Leipzig)* 332, 905–954 (1908).
- [52] H. Weisel, "Über die nach Fresnelscher Art Beobachteten Beugungserscheinungen der Gitter," *Ann. Phys. (Leipzig)* 338, 995–1031 (1910).
- [53] M. Wolfke, "Über die Abbildung eines Gitters Au erhalt der Einstellebene," *Ann. Phys. (Leipzig)* 345, 194–200 (1913).
- [54] R. Leggat, Talbot, William Henry Fox, <http://www.rleggat.com/photohistory/history/talbot.htm> (2000).
- [55] S. A. Akhmanov, A. P. Sukhorukov, and A. S. Chirkin, "Nonstationary phenomena and space-time analogy in nonlinear optics," *Sov. Phys. JETP* 28(4), 748–757 (1969).
- [56] T. Jansson and J. Jansson, "Temporal self-imaging effect in single-mode fibers," *J. Opt. Soc. Am.* 71, 1373–1376 (1981).
- [57] J. A. Bolger, P. Hu, J. T. Mok, J. L. Blows and B. J. Eggleton, "Talbot self-imaging and cross-phase modulation for generation of tunable high repetition rate pulse trains," *Opt. Commun.* 249, 431–439 (2005).
- [58] G. P. Agrawal, "Nonlinear fiber optics, Burlington," US: Elsevier, (2006).
- [59] D. Marcuse, "Light Transmission Optics." (Van Nostrand Reinhold, New York, 1982), Chaps. 8 and 12.
- [60] S. A. Akhmanov, V. A. Vysloukh, and A.S. Chirkin, "Optics of Femtosecond Laser Pulses," (American institute of Physics, New York, 1992), Chap. 1.
- [61] L. Oxenløwe, M. Galili, H. H. Mulvad, H. Hu, J. L. Areal, E. Palushani, H. Ji, A. Clausen and P. Jeppesen, "Nonlinear optical signal processing for Tbit/s Ethernet applications," *Int. J. Opt.*, 11, pp. 573843(1-14) (2012).
- [62] L. N. Binh and N. Q. Ngo, "Ultra-Fast Fiber Lasers, Principles and Applications with MATLAB Models," Boca Raton, FL, USA: CRC Press, (2011).
- [63] H. G. d. Chatellus, E. Lacot, O. Hugon, O. Jacquin, N. Khebbache and J. Azaña, "Phases of Talbot patterns in angular self-imaging," *J. Opt. Soc. Am. A* 32, 1132-1139 (2015).
- [64] J. Caraquitená, M. Beltrán, R. Llorente, J. Martí, and M. A. Muriel, "Spectral self-imaging effect by time-domain multilevel phase modulation of a periodic pulse train," *Opt. Lett.* 36(6), 858-860 (2011).

- [65] J. Wen, Y. Zhang, and M. Xiao, "The Talbot effect: recent advances in classical optics, nonlinear optics, and quantum optics," *Adv. Opt. Photon.* 5(1), 83-130 (2013)
- [66] F. Castles, "Linear electro-optic effects due to high-order spatial dispersion," *Phys. Rev. A*, 92, 063804 (2015).
- [67] H. Huang, S.R. Nuccio, Y. Yue, J.Y. Yang, Y. Ren, C. Wei, G. Yu, R. Dinu, D. Parekh, C.J. Chang-Hasnain, and A.E. Willner, "Broadband modulation performance of 100-GHz EO polymer MZMs," *J. Lightwave Technol.* 30, 3647-3652 (2012).

CHAPTER TWO: PROGRAMMABLE PASSIVE TALBOT OPTICAL WAVEFORM AMPLIFIER

2.1 Abstract

We introduce and experimentally demonstrate a new design for passive Talbot amplification of repetitive optical waveforms, in which the gain factor can be electrically reconfigurable. The amplifier setup is composed of an electro-optic phase modulator followed by an optical dispersive medium. In contrast to conventional Talbot amplification, here we achieve different amplification factors by using combinations of fixed dispersion and programmable temporal phase modulation. To validate the new design, we experimentally show tunable, passive amplification of picosecond optical pulses with gain factors from $m=2$ to 30 using a fixed dispersive line (a linearly chirped fiber Bragg grating).

2.2 Introduction

Amplification of signal intensity, including short optical pulses, is crucial for initiating physical processes, sensing, communications, measurement, and information processing [1, 2]. In traditional amplification methods, external power sources are conventionally used to multiply incoming signal carriers in order to deliver a higher intensity signal at the output through an active gain process [3, 4]. In contrast, passive amplifiers have been shown to amplify repetitive input waveforms (e.g. optical pulses) without using active gain through coherent waveform addition [5]. Here, a repetitive input waveform train is stored and coherently added to itself in a high-finesse cavity to build up fewer, replica, amplified waveforms at the output. The new waveforms are strengthened by the amount of repetition rate reduction. Nevertheless, this method requires ultra-precise active phase control of the input signal envelope and carrier, which is often impractical outside of a laboratory environment. Recently, we reported on a simple, all-fiber passive amplification technique for repetitive waveforms without using active gain [6], and demonstrated input-to-output gain and temporal noise mitigation of picosecond optical pulses in a Talbot amplifier [7]. Our technique is based on lossless repetition-rate division of the input periodic waveform (pulse) train through a dispersion-induced Talbot effect, inherently leading to intensity amplification of the input individual waveforms. Similar to cavity-based methods, the output waveform is amplified by the rate-division factor (without considering

practical insertion losses). Nevertheless, our previous design used a fixed length of dispersive medium for a given gain factor, requiring a change of dispersive device, and therefore a significant modification in the experimental setup, to tune the amplifier gain. As for any amplification approach, the capability of tuning the amount of gain provided by the amplifier is crucial. In amplified systems, unexpected changes in input signal power are often corrected simply by tuning amplifier gain, eliminating the need to physically change, tune, or adapt upstream components. Additionally, adaptive gain and gain-modulation are highly desirable for signal control and processing [8, 9].

Recently, we have introduced a new design for a passive Talbot amplifier, in which the gain factor can be electrically reconfigurable while using a fixed amount of dispersion [10]. In particular, similarly to our previous Talbot amplification design in [6], the amplifier setup is composed by an electro-optic phase modulator followed by an optical dispersive medium. In contrast to this previous work, by generalizing the equations for the required phase modulation and dispersion, we are able to obtain a range of various gain factors using a fixed dispersive element, i.e., a linearly chirped fiber-Bragg grating (LC-FBG) in our experiments. Programming the gain factor is then entirely achieved by the temporal phase modulation step. In this letter, we provide a comprehensive analysis of the theoretical background and design equations for programmable Talbot amplification. We further verify our model by amplifying repetitive, picosecond optical pulses generated from a pulsed fiber laser with tunable gain factors ranging from $m=2$ to 30 using a fixed dispersive element. Specifically, the new design of the Talbot amplifier is demonstrated through successful proof-of-concept experiments, amplifying repetitive, picosecond optical pulses generated from a pulsed fiber laser with tunable gain factors ranging from $m=2$ to 30

2.3 Principle of operation

Figure 2.1 shows the operation principle of our amplification technique. In the standard temporal Talbot effect, a flat-phase repetitive input waveform with repetition period T_0 (input signal at $z=0$) is self-imaged after dispersive propagation through every integer Talbot distances $(q+1)z_T$, where $q=0, 1, 2, \dots$ is a free design parameter. This can be seen on both the Talbot carpets 1 (a) and 1 (b) where inputs at repetition periods T' and T'' show self-images every Talbot distance $z_{T'}$ and $z_{T''}$, respectively. Recall that the fundamental integer Talbot distance depends on the input rate period and dispersion parameter as follows (e.g., for the top carpet in Fig.

2.1(a)): $z_T' = T'^2 / 2\pi\phi_2$, where ϕ_2 is the amount of first-order dispersion. There also exists an infinite amount of fractional distances, defined by the “Talbot Carpet” [11-15], where one can observe rate-multiplied self-images of the input waveform train (fractional Talbot effect), with correspondingly reduced individual waveform intensity. The examples in Fig. 2.1(a) at Talbot distances $z_T'/3$ and $z_T'/2$, have intensities reduced by the factors by which the repetition rate is multiplied, $m=3$ and $m=2$, respectively. Notice that in general, an input repetition rate $1/T_0$ is multiplied by a factor m ($=2, 3, 4, \dots$) at any fractional Talbot distance $(s/m)z_T$, where s is any integer coprime with m . In an integer Talbot self-image, the uniform phase profile of the input is restored, as can be seen e.g., in the self-imaged pulses at a distance z_T' in the top carpet (phase profiles represented by the dashed blue lines). However, the rate-multiplied self-images are affected by deterministic pulse-to-pulse residual phase, such as those observed at $z_T'/3$ and $z_T'/2$.

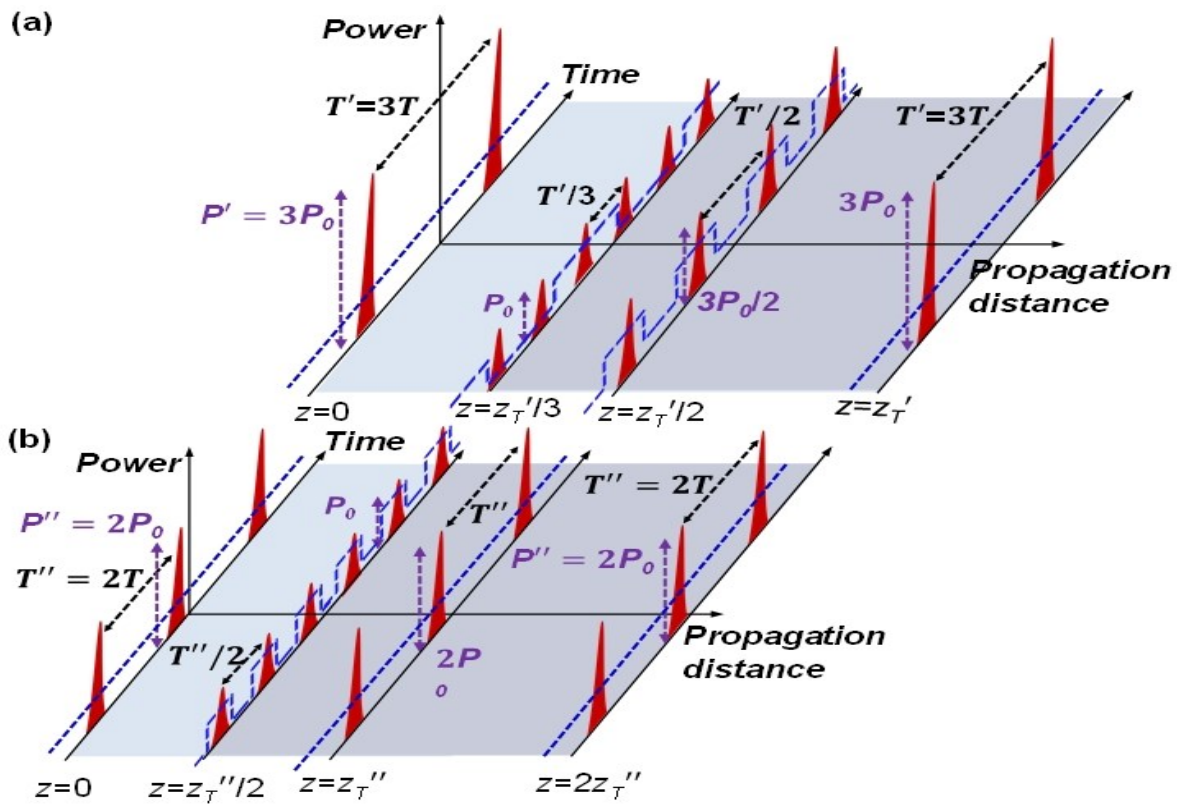


Figure 2.1-Concept for programmable Talbot amplification: (a) Talbot carpet when the input repetition period $T' = 3T$ (b) Talbot carpet when the input repetition period $T'' = 2T$. Pulse trains with repetition period T , at $z = z_T'/3$ and $z = z_T''/2$, result in different amplification factors using the same amount of dispersive delay (purple shading). The dashed blue lines represent the phase profiles of each of the temporal pulse trains in the carpet.

In previous demonstrations of Talbot amplification [6], we precondition an input pulse train to mimic the repetition rate and temporal phase of rate-multiplied self-images, such as those at $z_T'/3$ and $z_T'/2$. By propagating these pulse trains to the nearest self-image distance z_T' , we amplify the pulse train intensity by the amount of repetition rate reduction. In the cases where preconditioned inputs are made to match the pulse train at $z_T'/3$ and $z_T'/2$, amplification factors of the output train are $m=3$ and $m=2$, respectively. Fig. 2.2 shows how a fiber-integrated electro-optic phase modulator can be used to electronically program the desired phase profile for intensity amplification. However, in our previous design [6], each amplification factor requires a new dispersion value, typically implemented by physically changing the dispersive element (spool of fiber, fiber Bragg grating, etc.). As illustrated in Figure 2.2, our new design enables tuning the amplification factor by simply changing the temporal phase modulation profile, without modifying the dispersion amount. Figure 2.1 shows the concept of achieving programmable amplification factors using the same dispersive delay. The idea can be understood through a comparison of the two different Talbot carpets shown in Fig. 2.1(a) and Fig. 2.1(b), each corresponding to a different input repetition period, $T'=3T$ and $T''=2T$. Both carpets show the same repetition rate, T , at fractional Talbot distance $z_T'/3$, and $z_T''/2$, respectively. If we precondition an input pulse train to match the waveforms at these fractional distances (same period, T , but different residual temporal phase), propagation through the same amount of dispersive delay (purple shading) will result in a flat-phase output pulse train with amplification factors $m=3$ and $m=2$, respectively. In this example, the same dispersive propagation distance required for both amplification factors is $2z_T'/3=3z_T''/2=T'^2/3\pi\phi_2$. Notice that to ensure the same propagation length in the two cases, we select the first integer Talbot plane ($q=0$) in the top carpet but the second integer Talbot plane ($q=1$) in the bottom carpet.

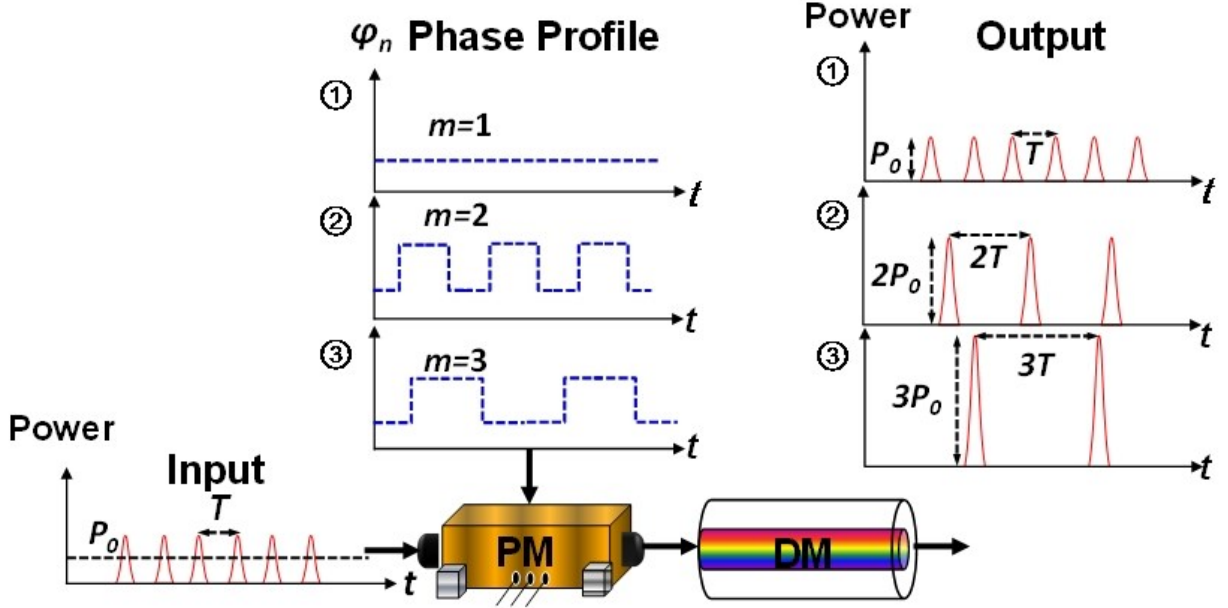


Figure 2.2-Method for phase preconditioning pulse trains for dispersion-induced temporal Talbot amplification. PM: phase modulator. DM: dispersive medium.

This example provides the needed guidelines to obtain the generalized equations for programmable Talbot amplification of an input waveform train, with a repetition period equal to T , by a gain factor of m ($=2, 3, 4, \dots$). For our derivations, we assume the general input plane location in the Talbot carpet to be at $(s/m)z_T$, where z_T is the fundamental integer Talbot distance corresponding to an input period equal to m times the period T , ($T_0 = m \times T$), and we recall that s is an integer and co-prime with m . Similarly, the general output plane location is at $(q+1)z_T$, with $q=0, 1, 2, \dots$. In general, in order to passively amplify a waveform train under the stated conditions, the required amount of dispersion can be calculated as that corresponding to propagation from the above-defined input location to the output in the Talbot carpet, namely

$$\phi_2 = (qm + m - s)mT^2 / 2\pi \quad (2.1)$$

The input waveform train should be phase modulated according to the Talbot phase modulation function corresponding to the input location $(s/m)z_T$ in the carpet, namely [16]

$$\varphi_n = -2(s/m) \left(\left[\frac{1}{s} \right]_m \right)^2 \pi n^2 \quad (2.2)$$

when $(s \cdot m)$ is even, and

$$\varphi_n = -2(s/m) \left[\frac{1}{2} \right]_m \left(\left[\frac{1}{2s} \right]_m \right)^2 \pi (2n+m)^2 \quad (2.3)$$

when $(s \cdot m)$ is odd, and where $[1/a]_b$ is the inverse of a modulo b . In these equations, $m=2, 3, 4, \dots$ is the gain factor and $n=0, 1, 2, \dots$ is the pulse number. The phase function in Eq. (2) is known to be periodic with fundamental period equal to m , namely $\varphi_n = \varphi_{n+m}$. Such a temporal phase modulation creates m times as many frequency tones in the spectrum of the input signal, leading to a comb frequency spacing that is reduced by m times with respect to the input, a process that is known as the spectral self-imaging effect [17]. If these phase shifts are reduced to a 2π range, a periodic sequence of discrete phase steps in the range $[0, 2\pi]$ is obtained. It is worth mentioning that setting $s = m-1$ and $q=0$ in the generalized equations in Eq. (1) and Eq. (2) gives rise to the conventional dispersion equation ($\phi_2 = mT^2/2\pi$) and application of the temporal phase-modulation profile ($\varphi_n = (m-1/m)\pi n^2$) previously defined for conventional Talbot amplification, as reported in [6].

Let us now consider the situation where we choose a maximum gain factor $m=M$. The corresponding required dispersion value by setting $q=0$ and $s = m-1$ is $\phi_2 = mT^2/2\pi$. Indeed, for a prescribed input temporal period T , we can now use the same dispersion value for a wider range of gain factors, satisfying $\phi_2 = (qm + m - s)mT^2/2\pi = MT^2/2\pi$, according to Eq. (1) above. In this equation, s and q are free design parameters, and as such, we can obtain a number of different gain factors m , being smaller or equal to M ($m \leq M$), that satisfy this condition for a given s and q . The required phase modulation function can be then obtained using Eq. (2) with the corresponding m and s factors.

2.4 Experimental results

In what follows, we will provide experimental results for demonstration of a passive Talbot amplifier of picosecond optical pulses, providing a programmable set of gain factors. In particular, we demonstrate gain factors of $m=2, 3, 5, 6, 10, 15$, and 30 by implementing a design with $M=30$, with corresponding $s=1, 2, 4, 1, 7, 13$, and 29 , and $q=7, 3, 1, 0, 0, 0$, and 0 , respectively. As illustrated in Fig. 2.3, we use an active MLL to generate uniform-phase, ~ 5 -ps (intensity full-width at half maximum, FWHM), Gaussian-like pulses at a wavelength of 1550 nm. In order to minimize the effect of group delay ripples in the LC-FBG used as a dispersive stage,

the input pulse bandwidth is reduced to ~ 0.200 nm (FWHM) with a Gaussian-like band-pass filter, thereby increasing the input pulse width into the Talbot amplifier to ~ 17 ps (FWHM). The input optical pulse is phase-modulated by a 40-GHz bandwidth electro-optic phase modulator, which is driven by a 7.5-GHz bandwidth electronic AWG. After temporal modulation, pulses are input into the LC-FBG, providing a fixed first-order dispersion with coefficient $\phi_2=12,926$ ps²/rad ($\sim 10,134$ ps/nm) over the entire input pulse bandwidth. All temporal intensity waveforms are measured by a 500-GHz optical sampling oscilloscope (OSO) and all spectra are measured by an optical spectrum analyzer (OSA) with a resolution of 0.4 pm.

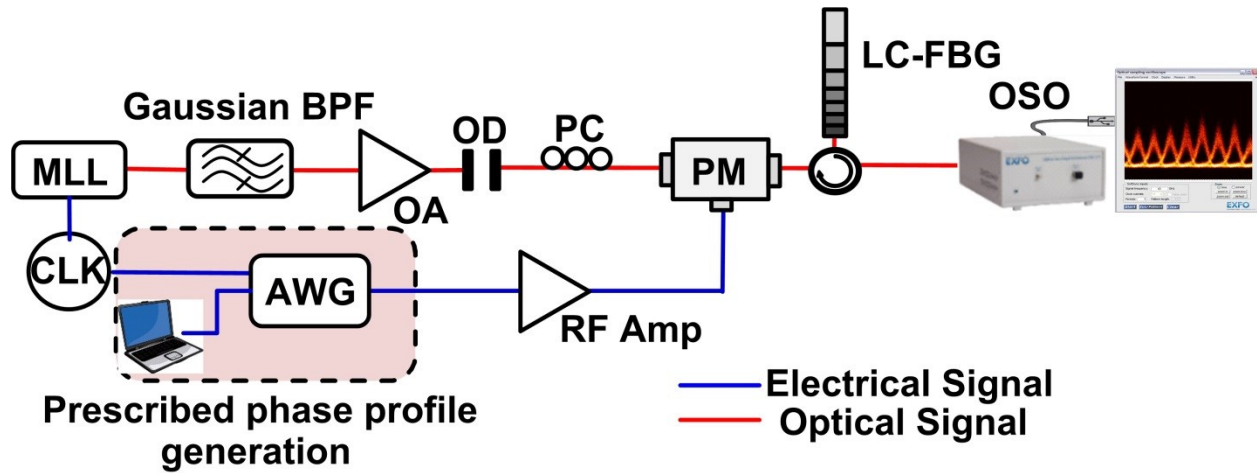


Figure 2.3-Experimental setup. MLL: mode-locked laser, BPF: band-pass filter, OA: optical amplifier, OD: optical delay line, PC: polarization controller, PM: phase modulator, LC-FBG: linearly chirped fiber Bragg grating, CLK: radio frequency clock source, AWG: arbitrary waveform generator, RF Amp: radio frequency (RF) amplifier.

Fig. 2.4 and 2.5 shows experimental results for our system. Because our central aim is to leave the dispersion fixed, we choose the repetition rate of the input pulse train, using Eq. (1), to allow the best possible range of tunable amplification factors. In particular, we select the repetition rate to be 19.2 GHz ($=1/T= (M/2\pi\phi_2)^{1/2}$), for a target maximum amplification factor of $M=30$ (enabling the programmable gain factors defined above).

Fig. 2.4(a) shows the prescribed electro-optic phase modulation profiles applied to the input optical pulses for the different gain factors demonstrated in the experiment ($m=2, 3, 5, 6, 10, 15,$ and 30 , from top to bottom). The dashed black lines show the ideal prescribed phase profiles, calculated from Eq. (2), and the solid green lines show the actual phase drives delivered by the AWG, captured with a 40-GHz electronic sampling scope. Fig. 2.4(b) shows the measured optical spectra of the input data signal before and after temporal phase modulation, showing the predicted spectral self-imaging effect, leading to the anticipated decrease in the comb frequency

spacing of the input signal by the amplification factor of m . The dashed horizontal arrow shows the same spectral span of 0.154 nm, corresponding to the input repetition rate of 19.2 GHz. Fig. 2.5 shows the temporal intensity waveforms of the input pulse trains (dashed grey) and the resultant amplified pulse trains (solid red) at the output of the dispersive medium (LC-FBG). Note that in each case, the repetition rate of the input is divided by the amplification gain factor m .

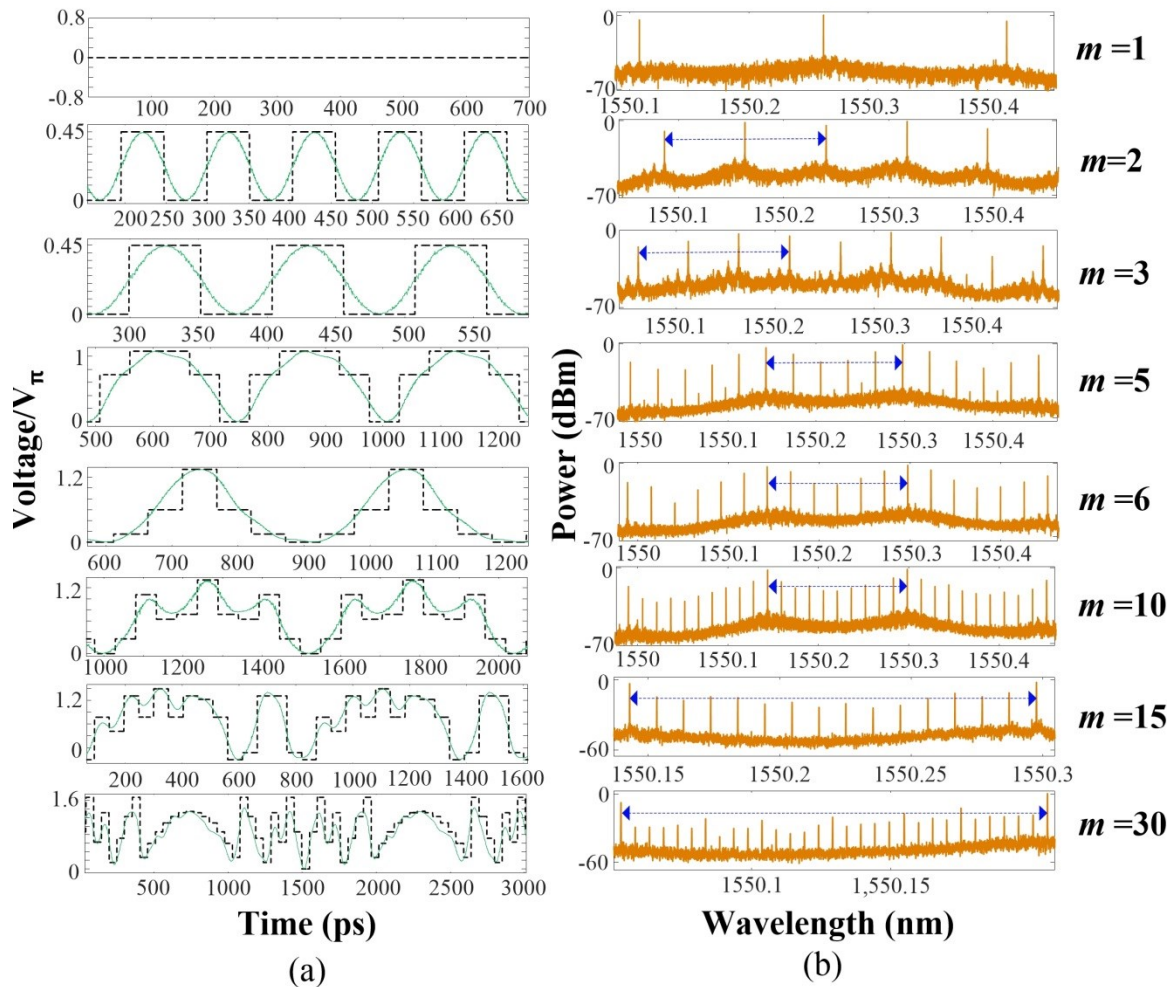


Figure 2.4-Experimental results of the demonstrated programmable passive amplifier. (a) Prescribed temporal phase profile. The dashed black lines: Ideal temporal phase profile. The solid green lines: Actual phase profile drive generated from the AWG. (b) Measured optical spectra of the optical pulse trains after temporal phase modulation. Dashed, blue, double-arrow shows a 0.154-nm (19.2-GHz) span.

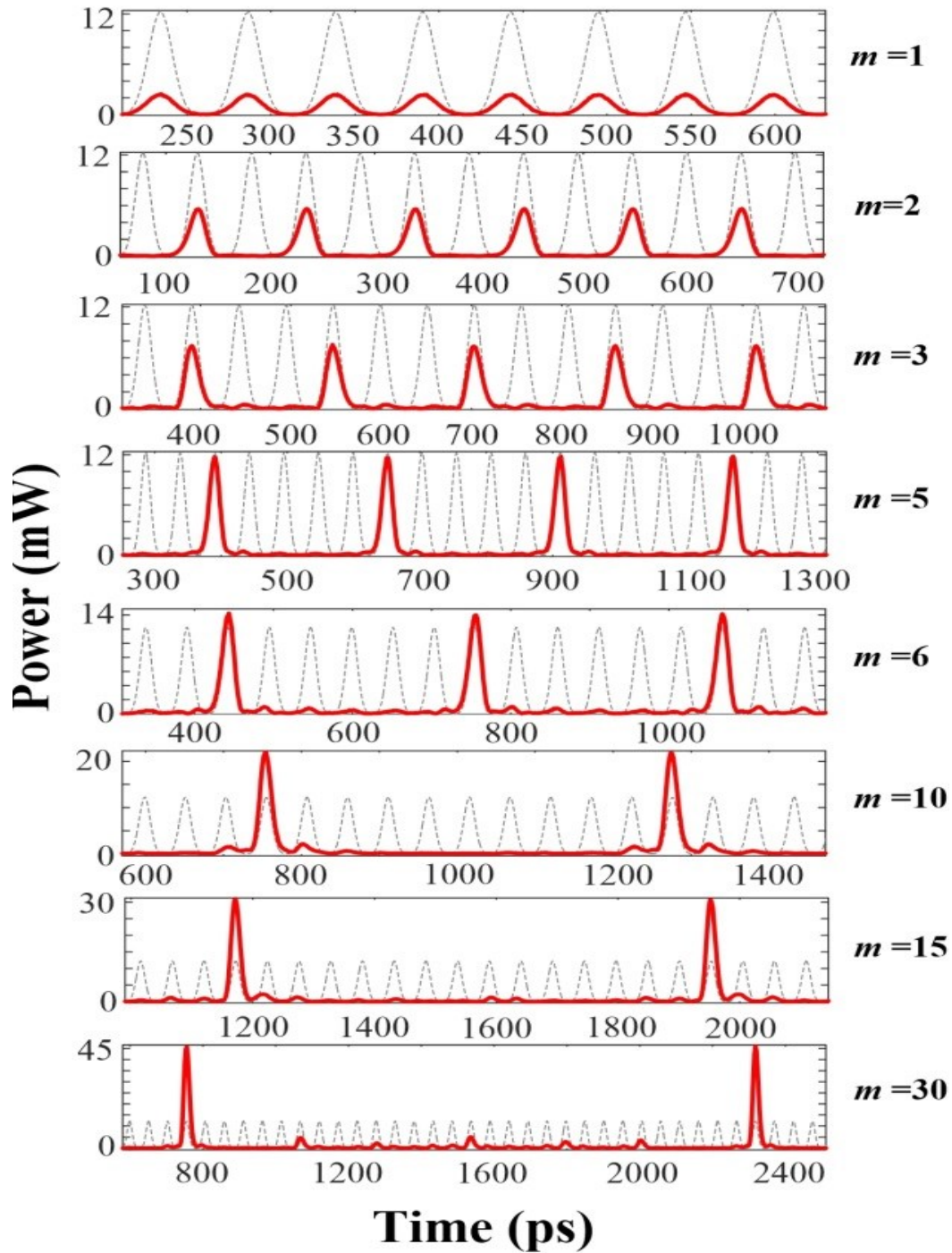


Figure 2.5-Experimental results of the demonstrated programmable passive amplifier. Temporal traces of the input and amplified output pulses (Input: dashed gray, Output: solid red), measured using a 500-GHz sampling oscilloscope.

As one can see in Fig. 2.6, correspondingly, the output pulses are amplified in intensity according to the predicted gain factor over an output power value that is lower with respect to

the input by the insertion loss of the amplifier (phase modulator and LC-FBG), i.e., by ~ 6 dB. Input-to-output gain is achieved when the passive Talbot gain (m) exceeds the system insertion loss, namely for experimental Talbot gain values of $m=6, 10, 15,$ and 30 . As expected, the output temporal pulses are nearly undistorted copies of the input pulses, with a measured FWHM time-width around 17 ps in all cases. Because our programmable amplifier is based on noiseless repetition-rate division of the input periodic waveform, the signal-to-noise ratio remains unchanged regardless of changing the amplification factor m [6]. In fact, any Talbot-based amplification technique will also show noise reduction in pulse-to-pulse intensity fluctuations and timing-jitter [7].

The slight mismatch between input and output pulse shapes can be mainly attributed to the deviation of the actual dispersion value used in experiments from the ideal Talbot condition [18], as well as to the mismatch from the ideal temporal phase modulation drives, see Fig. 2.4(a). The gain factors that are achieved in the experiments for all cases up to $m=15$ are very close to those theoretically expected with a slight deterioration for higher gain values. For instance, the measured gain factor (output to input pulse peak power ratio, after extracting insertion losses) for the case $m=15$ is 12.54 , just a 17% below the ideal gain value. The gain reduction is more significant in the case $m=30$, for which the measured amplification factor is ~ 18.37 . This deterioration in the actual gain with respect to the ideal one is associated with the pedestal that is observed in the output pulses, and it is mainly attributed to the intrinsic time-resolution limitation of the AWG, which fails to reproduce the ideal temporal phase drive for more complicated phase patterns (i.e., for higher values of m). Though the prescribed phase drive shows the same phase values over entire pulse bit-slots, we note that this technique only requires the correct constant phase over the pulse width, providing a high-tolerance to errors in the phase drive. This allows us to use a 7.5 -GHz AWG to effectively manipulate a 19.2 -GHz signal, pulse-by-pulse. Pulse pedestal can be reduced, thereby increasing energy in the main pulse, by using a higher-bandwidth AWG to better emulate the theoretical phase drive, as well as more carefully matching the temporal Talbot dispersion conditions.

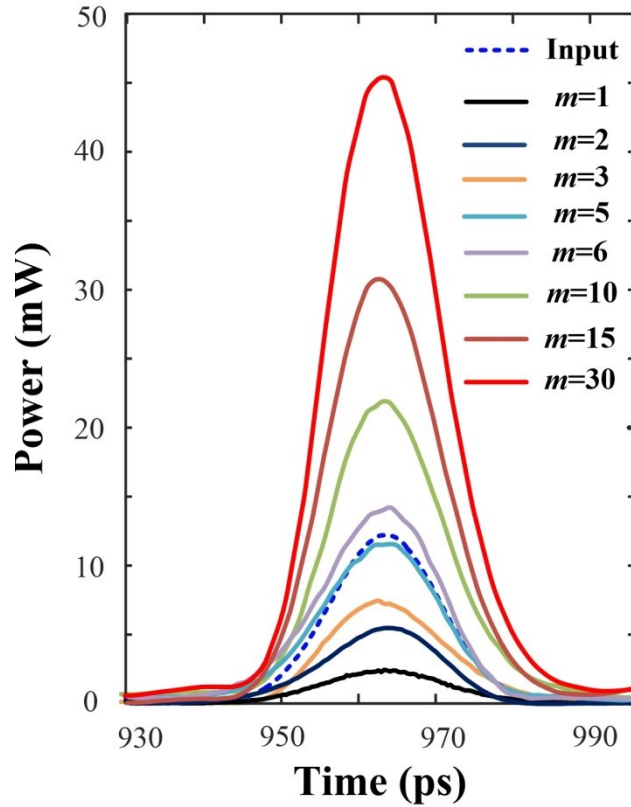


Figure 2.6- Superimposed single temporal pulse waveforms measured at the system output for the different amplification factors achieved in the experiment.

2.5 Conclusion

In conclusion, we have demonstrated a new simple, flexible design for passive amplification of repetitive pulse waveforms. The key feature of this design is that it allows for tunable gain without physically changing the experimental setup. Unlike previous approaches, here the dispersive medium is fixed and the amplification factor can be programmed electronically by modifying the temporal phase modulation profile according to the analytic equation in Eq. (2). Our proof-of-concept experiments have successfully shown in-fiber amplification of picosecond optical pulses with tunable gain factors in situ from 2 to 30, indicating a robust technique with many potential advantages.

2.6 References and links

- [1] F. Helmchen and W. Denk, "Deep tissue two-photon microscopy," *Nat. Methods* 2(12), 932-940 (2005).
- [2] J. Cheng, C.-Liu, S. Shang, D. Liu, W. Perrie, G. Dearden, and K. Watkins, "A review of ultrafast laser materials micromachining," *Opt. Laser Technol.* 46, 88-102 (2013).
- [3] P. C. Becker, N. A. Olsson, and J. R. Simpson, "Erbium-Doped Fiber Amplifiers: Fundamentals and Technology," (Academic Press, San Diego, CA, 1999).
- [4] R. P. Beardsley, A. V. Akimov, M. Henini, and A. J. Kent, "Coherent Terahertz Sound Amplification and Spectral Line Narrowing in a Stark Ladder Superlattice," *Phys. Rev. Lett.* 104(8), 085501-1-085501-4 (2010).
- [5] R. J. Jones and J. Ye, "Femtosecond pulse amplification by coherent addition in a passive optical cavity," *Opt. Lett.* 27(20), 1848-1850 (2002).
- [6] R. Maram, J. van Howe, M. Li, and J. Azaña, "Noiseless intensity amplification of repetitive signals by coherent addition using the temporal Talbot effect," *Nat. Commun.* 5, 5163 (2014), doi:10.1038/ncomms6163.
- [7] R. Maram, M. Seghilani, J. Jeon, X-Z. Li, L. Romero Cortés, J. van Howe, and J. Azaña, "Demonstration of input-to-output gain and temporal noise mitigation in a Talbot amplifier," *Photon. Technol. Lett.* in press (2018).
- [8] A. Rostami, H. Baghban, and R. Maram, "Nanostructure semiconductor optical amplifiers: building blocks for all-optical processing," Springer-Verlag (2011).
- [9] N.K. Dutta and Q. Wang, "Semiconductor Optical Amplifiers," World Scientific (2006).
- [10] J. Jeon, R. Maram, J. van Howe, and J. Azaña, "Programmable passive waveform amplifier based on temporal self-imaging effects," Conference on Lasers and Electro-Optics (CLEO), San Jose, USA, paper: SF2L.1 (2017).
- [11] J. Azaña and M. A. Muriel, "Temporal self-imaging effects: theory and application for multiplying pulse repetition rates," *IEEE J. Sel. Top. Quant. Electron.* 7(4), 728-744 (2001).
- [12] T. Jansson and J. Jansson, "Temporal self-imaging effect in single-mode fibers," *J. Opt. Soc. Am.* 71(11), 1373-1376 (1981).
- [13] F. Mitschke and U. Morgner, "The temporal Talbot effect," *Opt. Photon. News* 9(45), 45-47 (1998).
- [14] J. Bolger, P. Hu, T. Mok, J. Blows, and B. Eggleton, "Talbot self-imaging and cross-phase modulation for generation of tunable high repetition rate pulse trains," *Opt. Commun.* 249(4-6), 432-439 (2005).

- [15] J. Wen, Y. Zhang, and M. Xiao, "The Talbot effect: recent advances in classical optics, nonlinear optics, and quantum optics," *Adv. Opt. Photon.* 5(1), 83-130 (2013).
- [16] H. G. de Chatellus, E. Lacot, O. Hugon, O. Jacquin, N. Khebbache, and J. Azaña, "Phases of Talbot patterns in angular self-imaging," *J. Opt. Soc. Am. A* 32(6), 1132-1139 (2015).
- [17] J. Caraquitena, M. Beltrán, R. Llorente, J. Martí, and M. A. Muriel, "Spectral self-imaging effect by time-domain multilevel phase modulation of a periodic pulse train," *Opt. Lett.* 36(6), 858-860 (2011).
- [18] R. Maram, L. Romero Cortés, and J. Azaña, "Programmable fiber-optics pulse repetition-rate multiplier," *IEEE, J. Lightw. Technol.* 34(2), 5403–5406 (2016).

CHAPTER THREE: PROGRAMMABLE SUB-HARMONIC OPTICAL CLOCK RECOVERY

3.1 Abstract

We report on a simple, all-fiber design for a programmable base/sub-harmonic optical clock recovery circuit, to be employed in return-to-zero (RZ) transmission systems, in which the rate division factor can be electrically reconfigurable. The clock recovery scheme, involving a phase modulator and a fixed dispersive medium, exploits the dispersion-induced inverse temporal self-imaging effect (I-TSI). In contrast to previously reported TSI-based clock recovery methods, the required dispersion is fixed in this method and the desired clock division factors is tuned only by changing the temporal phase modulation profile. Proof-of-concept experiments are demonstrated to verify the proposed technique. In particular, we report successful clock extraction of 5.55-GHz, 2.22-GHz, and 1.11-GHz sub-harmonic clock signals as well as the 11.1-GHz base-rate clock signal from an 11.1-Gbit/s RZ-OOK binary on-off-keying (OOK) data signal.

3.2 Introduction

Optical clock recovery, extracting the timed clock from the received optical data signals, is an essential operation in high-speed optical communication, information processing and computing systems. In particular, base-rate clock recovery (BRCR) is indispensable for many key functions such as 3R regeneration [1] and general signal processing techniques [2]. Additionally, sub-harmonic clock recovery (SHCR), clock recovery at a reduced repetition rate with respect to the original data's base rate, is sought after for high speed synchronization that can be manipulated with lower-frequency electronics. For instance, SHCR is a fundamental functionality for demultiplexing and per-channel processing operations in optical time-division multiplexing (OTDM) systems [3].

Thus far, a wide variety of optical BRCR and SHCR techniques based on different physical principles have been proposed and demonstrated. Qiang Wang et al. and C. Ware et al. demonstrated novel schemes for clock recovery using a Mach-Zehnder modulator based on optoelectronic oscillator and a PPLN-based opto-electronic phase-locked loop, respectively [3],

[4]. Techniques based on the temporal self-imaging (TSI) effect [5]-[7], itself induced by group-velocity dispersion (GVD), have been studied as a lossless means to recover both the base-rate and sub-harmonic clock signals from aperiodic telecommunication data, particularly Return-to-Zero On-Off-Keying (RZ-OOK) optical data signals. Such TSI techniques show promise for realization of energy-efficient, single-platform signal regeneration and clock recovery sub-systems. In the past, TSI has been primarily employed for reproduction and repetition-rate multiplication of periodic pulse trains. We recently performed a reverse-engineering of the conventional Talbot effect, that is here referred to as “inverse temporal self-imaging (I-TSI) effect”, to develop an energy-preserving repetition-rate division technique,—the generation of lower repetition-rate pulses from a periodic higher repetition-rate pulse train [8]. Similar to the TSI, the I-TSI is based on the distributed interference of dispersed pulses, i.e., there is no direct one-to-one correspondence between the input and output pulses. As a consequence, we further demonstrated that this effect also possessed the inherent property to generate a periodic output (with sub-harmonic repetition rate) yet from an aperiodic input pulse train, allowing recovery of a sub-harmonic clock signal from RZ-OOK data [9].

Nevertheless, the SHCR shown in [9] employs a fixed length of dispersive medium for a given bit rate division factor, and consequently, this solution does not easily allow for tuning the repetition rate factor without physically changing the dispersive element. However, we recently experimentally demonstrated I-TSI for periodic waveform intensity amplification in which rate division factors can be electrically reconfigurable [10]. We anticipate that applying this new technique to clock-recovery from aperiodic data signals could therefore allow for SCHR and BRCC in a simple, electronically tunable setup.

In this communication, we demonstrate theoretically and experimentally a new design for Talbot-based sub-harmonic clock recovery (including BRCC) from optical pulsed (RZ) data signals, in which the rate division factor can be electrically reconfigurable. The proposed clock recovery setup is fairly simple, composed of an electro-optic phase modulator followed by a fiber-optics dispersive medium, Fig.3.1. Through a generalization of the known equations for I-TSI, we are able to readily tune the desired rate division factor only by programming the phase modulation function. A proof-of-concept experimental demonstration, supported by numerical analysis, is reported on an 11.1-Gbit/s RZ-OOK data signal. In particular, we report successful extraction of 5.55-GHz, 2.22-GHz, and 1.11-GHz sub-harmonic clock signals as well as the 11.1-GHz base-rate clock signal from an 11.1-Gbit/s RZ-OOK data signal under a 2^7-1 Pseudo-Random Bit Sequence (PRBS) pattern.

3.3 Principle of operation

Fig. 3.1 illustrates the concept of our programmable BR/SH CR technique. We effectively exploit I-TSI, which can be realized through a suitable combination of temporal phase modulation and GVD on the input data signal. The output signal is a recovered clock signal with $1/m$ the bit rate of the input signal (with $m = 1, 2, 3, \dots$). For the design of our programmable BR/SH CR circuit, we use the generalized equations recently derived for programmable passive amplification of purely periodic temporal waveforms (e.g., optical pulse trains) [10], which allow us to obtain different rate division factors with a fixed dispersive medium. Using this generalized design, the rate division factor (m) is electrically tunable from $m = 1$ (BR/CR) to higher natural values (SH/CR), and depends only on the temporal phase modulation profile applied on the input data signal. In particular, in order to recover the sub-harmonic clock signal of a RZ-OOK input signal, with bit period T (rate = $1/T$), by a clock division factor of m ($= 1, 2, 3, \dots$), the dispersive medium should introduce a total GVD value of

$$\phi_2 = (qm + m - s)mT^2 / 2\pi \quad (3.1)$$

where ϕ_2 is defined as the slope of the linear group delay as a function of radial frequency, s is an integer and co-prime with m , and $q = 0, 1, 2, \dots$. The corresponding bit-to-bit temporal phase modulation function ($n = \text{bit number}$) is

$$\varphi_n = -2(s/m) \left(\left[\frac{1}{s} \right]_m \right)^2 \pi n^2 \quad (3.2(a))$$

when $s \cdot m$ is even, and

$$\varphi_n = -2(s/m) \left[\frac{1}{2} \right]_m \left(\left[\frac{1}{2s} \right]_m \right)^2 \pi (2n + m)^2 \quad (3.2(b))$$

when $s \cdot m$ is odd, where $[1/a]_b$ is the inverse of a modulo b . These equations are a generalized form of those previously reported in Ref. [9], which can be recovered by setting $s = m-1$ and $q = 0$. Notice that if the phase shift φ_n is reduced to a 2π range, a periodic sequence of phase steps with a fundamental period equal to the rate division factor m is obtained. These phase shifts indeed induce a spectral self-imaging effect on the modulated data signal [8]. In particular, the temporal phase modulation process reduces the spectral comb spacing of the clock component (i.e. the spectral separation between two adjacent lines) of the input data signal by the rate division factor m . It should be mentioned that in the absence of temporal phase-modulation ($m =$

1), the dispersion ϕ_2 satisfies an integer TSI condition, and as such, it will produce an output clock signal at the basic input bit rate (i.e. BRCR) [6], [7].

To realize the programmable BH/SHCR, we first consider the situation where we choose a division factor of $m = M$ (M is maximum division factor). The corresponding required dispersion value by setting $q = 0$ and $s = M-1$ is $\phi_2 = MT^2/2\pi$. Indeed, for the same input bit rate period T , we can use this same dispersion value to achieve a wide range of repetition rate division factors, satisfying $\phi_2 = (qm+m-s)mT^2/2\pi = MT^2/2\pi$. In this equation, s and q are free design parameters, and as such, we can obtain a number of rate division factors m ($m \leq M$) that satisfy this condition for suitable values of the free parameters, s and q . The required temporal phase modulation function, φ_n , can then be obtained using Eq. (3.2) with the corresponding m and s factors. In short, programmable clock recovery is simply achieved by modulating the input temporal phase profile according to φ_n for the target m , and related s parameter, without changing the dispersive medium.

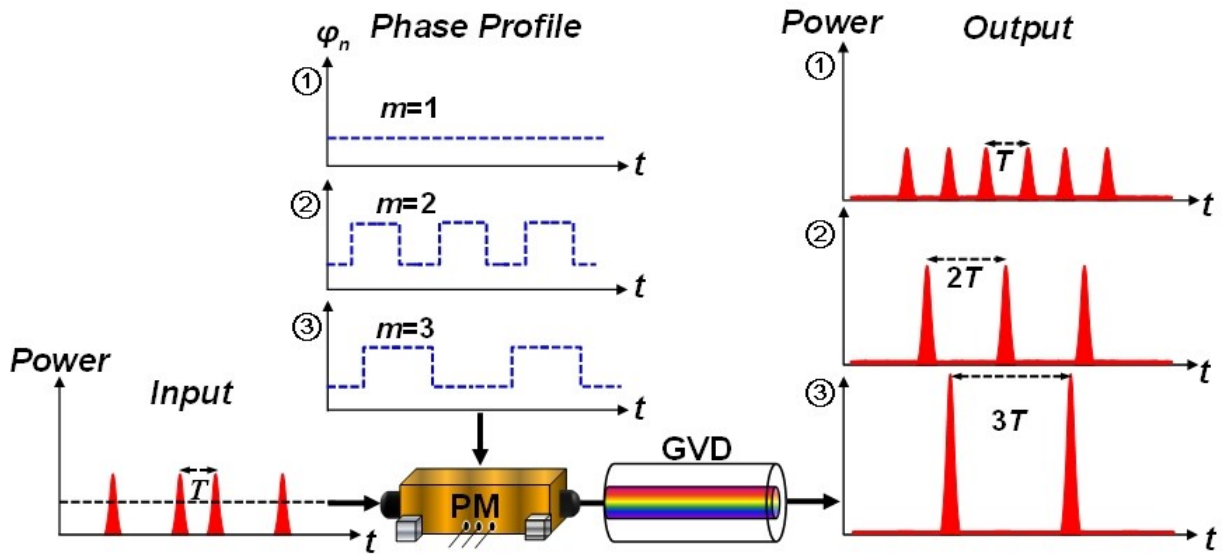


Figure 3.1-Operation principle illustration of the proposed programmable BR/SH CR concept. PM: temporal phase modulator. GVD: group-velocity dispersion.

The described operation principle has been first validated through numerical simulations for a programmable SHCR with rate division factors of $m = 2, 5, \text{ and } 10$, and choosing $M = 10$. Corresponding values for the parameters s and q are $s = 1, 3, \text{ and } 9$, and $q = 2, 0, \text{ and } 0$, respectively; see Fig. 3.2. As predicted, BRCR is also achieved in the absence of temporal phase-modulation (division factor of $m = 1$). In this example, we assumed an input RZ data signal consisting of 2-ps Full Width Half Maximum (FWHM) optical pulses at a bit rate of 11.1

Gbit/s, coded under a PRBS of $2^7 - 1$. Fig. 3.2 (a) shows the prescribed temporal phase profiles for the targeted SHCR factors of 1 (BRCR), 2, 5 and 10, respectively. Fig. 3.2 (b) shows the temporal waveforms of the input signal and output clock signals of 11.1 GHz ($m = 1$), 5.55 GHz ($m = 2$), 2.22 GHz ($m = 5$), and 1.11 GHz ($m = 10$), respectively. Fig. 3.2(c) shows the corresponding eye-diagrams, i.e., the persistent-mode temporal waveforms of the involved signals. The results clearly confirm that a periodic pulse train is recovered, as evidenced by the absence of baseline in the eye diagrams. However, some amplitude modulation of the extracted clock pulses is observed, particularly for lower division factors. If needed, this could be mitigated by incorporating a power equalizer [9].

The ability of temporal self-imaging to produce uniform amplitude optical pulses from the input RZ-OOK data signal directly depends on the number of spectral clock components in the input signal, namely the input pulse time-width [9]. In order to quantitatively evaluate the magnitude of pulse-to-pulse amplitude variations in the clock signal as a function of this parameter, we define the “relative amplitude variation factor (RAVF)” as the ratio of the difference between the highest pulse’s peak power (P_{max}) and the lowest pulse’s peak power (P_{min}) to the highest pulse’s peak power.

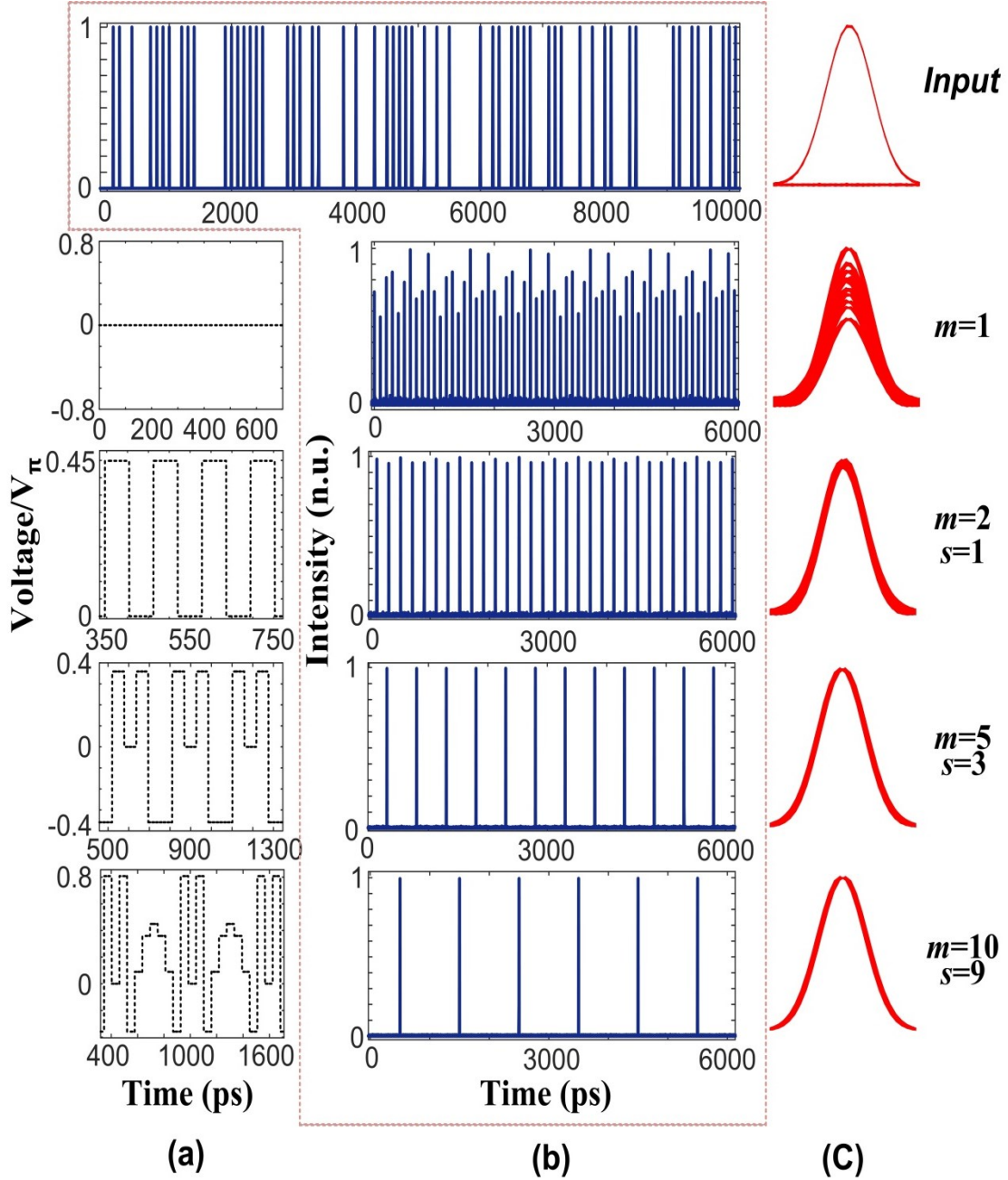


Figure 3.2-Numerical simulation results of the programmable BR/SH CR. (a) Ideal temporal phase modulation profiles derived from Eq. 3.2(a) and 3.2(b). (b) Temporal waveforms (data input on top). (c) Eye diagrams.

$$RAVF = \frac{P_{\max} - P_{\min}}{P_{\max}} \quad (3.4)$$

Figure. 3.3 shows the output $RAVF$ as a function of the input pulse time-width for different division factors, m . For any given m , the amplitude variations of the recovered clock pulses are

mitigated as the input pulse time-width decreases. This is consistent with the fact that a shorter input pulse width incorporates a larger number of spectral clock components towards the periodic pulse reconstruction process. Therefore, pulses spread out temporally more significantly (for the same amount of dispersion), and this induces inter-pulse interference among pulses that are further temporally apart pulses as well as among adjacent ones; as a result in average, the input pulses' energy is more uniformly redistributed over all the newly generated pulses. The red symbol represents the *RAVF* of the actual experimental data with an input pulse-width of 17 ps. The experimental *RAVF* is consistent with the theoretical prediction of *RAVF*.

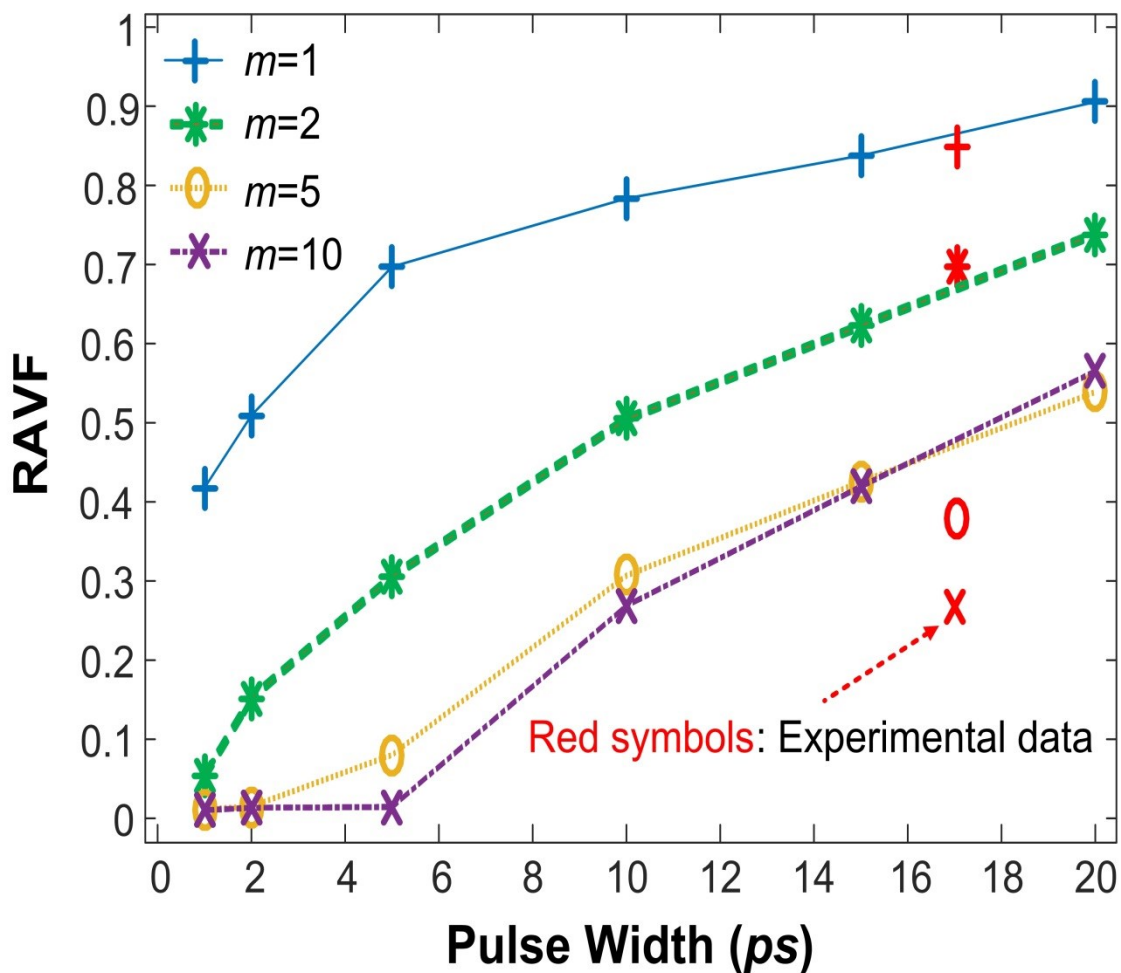


Figure 3.3-Sub-harmonic clock signal's amplitude-variations as a function of the input temporal pulse width for different bit rate-division factors (m). Estimates from the experimentally recovered waveforms are plotted in red.

3.4 Experimental result

We furthermore report on a proof-of-concept experiment to validate the proposed concept by performing sub-harmonic clock recovery from an 11.1-Gbit/s RZ-OOK data signal. The experimental setup is sketched in Fig. 3.4. The setup consists of three main blocks: (1) the transmitter to generate an 11.1-Gbit/s RZ-OOK input signal; (2) the sub-harmonic clock recovery circuit to recover the clock signals; and (3) the receiver to measure the temporal waveform and spectrum of the recovered optical clock signals. In the transmitter, the RZ-OOK data signal is produced by intensity modulation of ~ 17 ps (FWHM) optical pulses generated from an actively mode-locked laser (MLL) with an 11.1-GHz repetition rate at a central wavelength of 1550 nm. The intensity modulator (MZM) driver is a 2^7-1 PRBS, thus generating a RZ-OOK modulated signal. The generated data signal was then delivered to the clock recovery circuit, consisting of a 40-GHz bandwidth electro-optic phase modulator driven by arbitrary waveform generator (AWG: Tektronix AWG7122C, Sampling rate: 24 Gsamples/s, Bandwidth: 7.5 GHz), followed by a fixed dispersive medium, i.e., a LC-FBG, providing a GVD with coefficient $\phi_2=12,926$ ps²/rad ($\sim 10,134$ ps/nm) over the entire input pulse bandwidth. All the eye diagrams of the input and output clock signals are measured by a 500-GHz optical sampling oscilloscope (OSO), and all the optical spectra are measured by an optical spectrum analyzer (OSA) with a resolution of 0.4 pm.

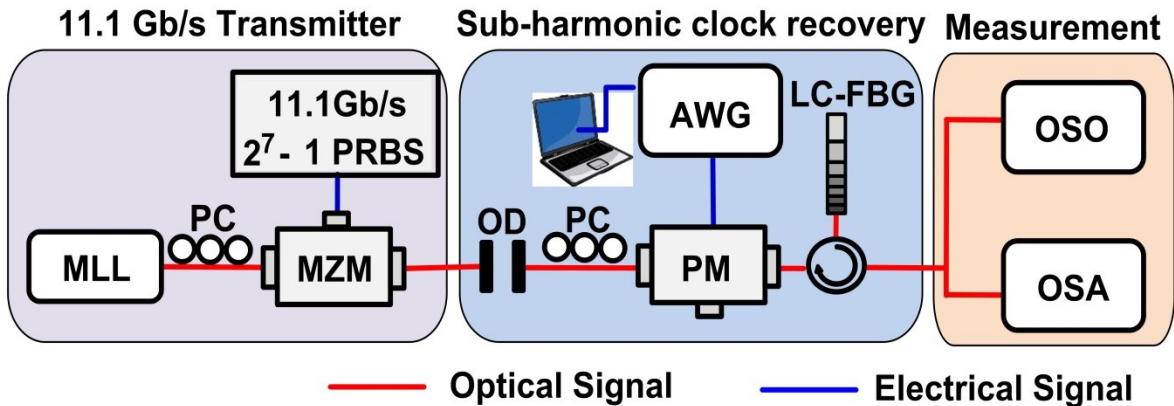


Figure 3.4-Experimental setup for the programmable BR/SHCR through dispersion induced temporal self-imaging. MLL: actively mode-locked laser, MZM: Mach-Zehnder modulator, OD: optical delay line, PC: polarization controller, PM: phase modulator, LC-FBG: linearly chirped fiber-Bragg grating, AWG: arbitrary waveform generator, OSO: optical sampling oscilloscope, OSA: optical spectrum analyzer.

Figure 3.5 presents the prescribed temporal phase profiles and the optical spectra of the input data signal and output clock signals. Fig. 3.5(a) shows the prescribed electro-optic phase

modulation profiles applied to the input optical pulses, for the cases when we target rate division factors for the SHCR of $m = 1, 2, 5,$ and $10,$ respectively. The dashed black lines show the ideal temporal phase profiles calculated from Eq. 3.2, and the solid green lines show the actual phase drives delivered by the electronic AWG. Fig. 3.5(b) shows the predicted spectral self-imaging effect due to the phase modulation step, leading to the expected decrease in the underlying periodic frequency comb spacing by the rate-division factors of $m = 1, 2, 5$ and $10,$ respectively. In this figure, the black dashed arrow shows the same frequency range (0.09 nm), corresponding to the input bit rate of 11 GHz.

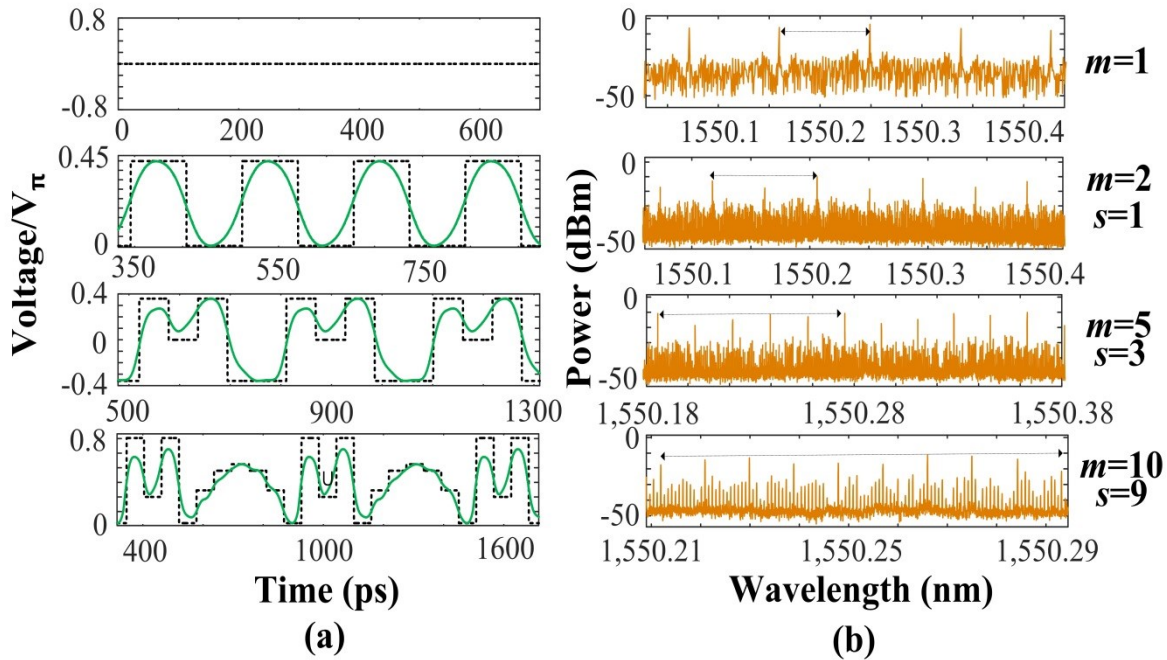


Figure 3.5-(a) Theoretically prescribed (dashed black) and experimentally implemented (solid green) temporal phase modulation profiles (b) Measured optical spectra at the output of the programmable BR/SH CR circuit, corresponding to the cases $m = 1, 2, 5,$ and $10.$ Dashed, black, double-arrow shows a 0.08-nm (11.1-GHz) span.

Finally, Fig. 3.6 shows the experimental results of optical clock recovery for the different bit rate-division factors of $m = 1, 2, 5$ and $10,$ including measurements corresponding to the input RZ-OOK data signal. In particular, Fig. 3.6(a) shows the measured temporal waveforms and eye-diagrams at the input (top plot) and output of the clock-recovery circuit for the cases of BR/SH CR at 11.1 GHz when $m = 1,$ and SHCR at 5.55 GHz, 2.22 GHz and 1.11 GHz, when $m = 2, 5,$ and $10,$ respectively. The temporal waveforms are captured by a 25-GHz electrical real-time oscilloscope and the eye diagrams are measured by a 500-GHz optical sampling oscilloscope (OSO). The results clearly show that a periodic optical pulse train is recovered at the system

output, as evidenced by the absence of a baseline in the eye diagrams, with a repetition rate equal to the input bit rate divided by the corresponding factor m . Fig. 3.6(b) shows the measured RF spectra corresponding to the temporal waveforms in Fig. 3.6(a). Clearly visible peaks appear at 11.1 GHz ($m = 1$), 5.55 GHz ($m = 2$), 2.22 GHz ($m = 5$), and 1.11 GHz ($m = 10$), confirming successful realization of the predicted BR/SHCR processes. The comparison of the input RF spectrum with the BR/SHCR RF spectra clearly shows that the data frequency components of the incoming pseudo-randomly intensity-modulated input signal (i.e. the components around and well beyond the base-rate clock frequency of 11.1 GHz) have been strongly suppressed through the clock recovery process. In fact, we note that the I-TSI process performs as a periodic RF bandpass filter with central frequencies located at $(mT)^{-1}$ GHz and its harmonics. The bandwidth of the RF bandpass filter (around each harmonic) is inversely proportional to the rate division factor m . As a result, as observed in Fig. 3.6(b), the RF spectral intensity of the data components is increasingly suppressed as the value for higher values of m . Obviously, a narrower bandwidth for the effective RF filtering process, and the related increased suppression of the data components in the RF spectra, are indications of a higher quality output clock signal, e.g., with lower pulse-to-pulse amplitude variations and an improved eye opening. Thus, the experimentally observed trends, particularly in regards to the amplitude modulation of the recovered periodic clock (*RAVF*) depending on the factor m , are in good agreement with the theoretical predictions in Fig. 3.3. The observed improvements in the experimentally achieved *RAVF* for the cases of $m = 5$ and 10, as compared with the theoretical predictions (see Fig. 3.3), may be attributed to the fact that the OSO-measured temporal waveforms (Fig. 3.6) used for the *RAVF* estimates are each averaged by 4 times.

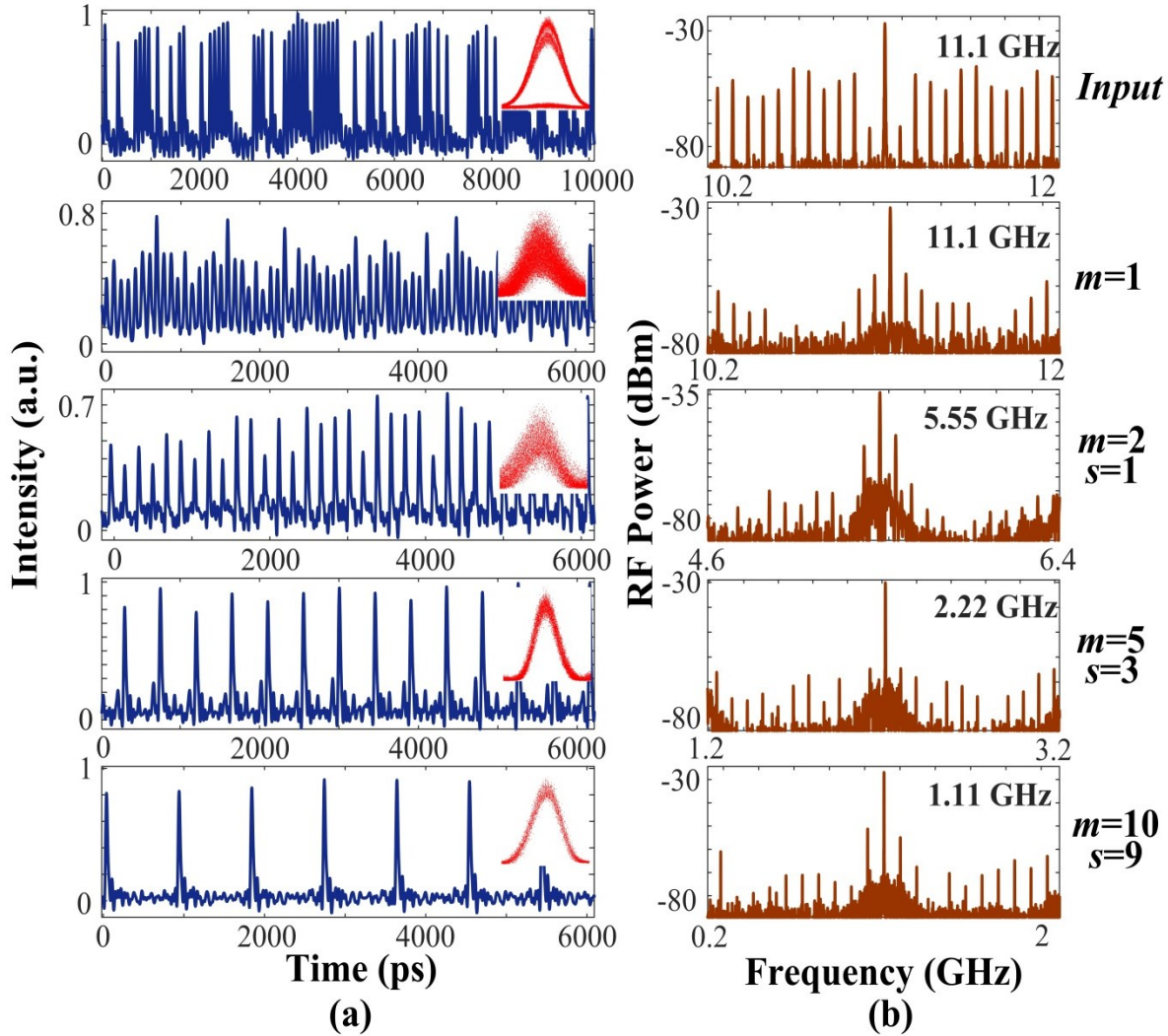


Figure 3.6-Experimental proof-of-concept results of the proposed programmable BR/SH CR concept. (a) Temporal waveforms and eye-diagrams of the input data signal and recovered optical clock when the system is programmed to achieve BR/SH CR ($m = 1$), and SHCR (for $m = 2, 5$, and 10). Temporal waveform measurements are averaged by 4 times. (b) Corresponding RF spectra of the signals shown in (a).

3.5 Conclusion

In conclusion, we have experimentally demonstrated a new design for programmable base-rate (BR) and sub-harmonic clock recovery (SH-CR) of RZ-OOK optical data signals based on the “inverse” temporal self-imaging (I-TSI) effect. Our technique only requires phase manipulations in the temporal domain and dispersive spectral filtering of the input data signal, and it allows one to tune electronically the recovered clock rate by programming the prescribed temporal phase modulation profiles. In particular, we have reported successful tunable clock extraction of 5.55-

GHz, 2.22-GHz, and 1.11-GHz sub-harmonic clock signals, as well as the 11.1-GHz base-rate clock, from a 2^7-1 PRBS 11.1-Gbit/s data signal. In addition to its potential practice interest towards the development of advanced optical clock recovery platforms, this work shows the unique capabilities enabled by the overall concept of electronically programmable I-TSI.

3.6 References and links

- [1] Z. Zhu *et. al*, "High-performance optical 3R regeneration for scalable fiber transmission system applications," *J. Lightw. Technol.*, vol. 25, no. 2, pp. 504–511, Feb. 2007.
- [2] T. Houbavlis *et. al*, "All-optical signal processing and applications within the Esprit project DO_ALL," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 781–801, Feb. 2005.
- [3] Q. Wang *et. al*, "Effective optical clock recovery and simultaneous fourfold demultiplexing of OTDM signal using an optoelectronic oscillator," *Opt. Express*, vol. 21, no. 24, pp. 3000–3001, Dec. 2013.
- [4] C. Ware *et. al*, "320 Gbps to 10 GHz sub-clock recovery using a PPLN-based optoelectronic phase-locked loop," *Opt. Express*, vol. 16, no. 7, pp. 5007–5012, Mar. 2008.
- [5] J. Azaña *et. al*, "Temporal self-imaging effects: theory and application for multiplying pulse repetition rates," *IEEE J. Sel. Top. Quant. Electron.*, vol. 7, no. 4, pp. 728–744, Aug. 2001.
- [6] C. R. Fernández-Pousa *et. al*, "Broadband noise filtering in random sequences of coherent pulses using the temporal Talbot effect," *J. Opt. Soc. Am. B*, vol. 21, no. 5, pp. 914–922, 2004.
- [7] D. Pudo *et. al*, "Single and multiwavelength all-optical clock recovery in single-mode fiber using the temporal Talbot effect," *J. Lightw. Technol.*, vol. 25, no. 10, pp. 2898–2903, Oct. 2007.
- [8] R. Maram *et. al*, "Noiseless intensity amplification of repetitive signals by coherent addition using the temporal Talbot effect," *Nat. Commun.* 5:5163 doi: 10.1038/ncomms6163 (2014).
- [9] R. Maram *et. al*, "Sub-harmonic periodic pulse train recovery from aperiodic optical pulse sequences through dispersion-induced temporal self-imaging," *Opt. Express*, vol. 23, no. 3, pp. 3602–3613, Feb. 2015.
- [10] J. Jeon *et. al*, "Programmable passive waveform Talbot optical amplifier," *Opt. Lett.*, 2017.

CHAPTER FOUR: CONCLUSION AND PERSPECTIVES

4.1 Conclusion

In this work, a comprehensive analysis, investigation and applications of inverse temporal self-imaging (I-TSI) effects in fiber-optics devices for the enhanced control of repetitive optical waveforms have been presented. In particular, we report a non-trivial generalization of the I-TSI equations (i.e., design equations for the phase modulation and dispersive stages), which allow us to obtain a relatively wide range of different gain factors or rate-division factors using a fixed dispersion, by suitably programming the temporal phase modulation step.

As the first objective of the work, a new design for programmable passive Talbot amplification of repetitive optical waveforms has been successfully demonstrated, in which the gain factor can be electrically reconfigurable. The amplifier setup is composed of an electro-optic phase modulator followed by an optical dispersive medium. Significant gain controlling was achieved without modifying the dispersive medium by using combinations of fixed dispersion and programmable temporal phase modulation. To validate the new design, proof-of-concept experiments successfully show in-fiber passive amplification of picosecond optical pulses with tunable gain factors ranging from $m = 2$ to 30, and no pulse distortion, using a fixed fiber-optics dispersive line (a linearly chirped fiber-Bragg grating), through electronic reconfiguration of the driving voltage in an electro-optic modulator. The presented results confirm the validity of the newly found, generalized equations and their practical application.

A second application based on the newly founded generalization of the Talbot-based amplification equation is also presented. A simple, all-fiber design for a programmable base/sub-harmonic optical clock recovery circuit has been reported to be employed in return-to-zero (RZ) transmission systems, in which the recovered clock rate can be electrically reconfigurable. The clock recovery scheme, involving a phase modulator and a fixed dispersive medium, exploits again the dispersion-induced I-TSI effect. However, in previous designs, a different rate division factor necessarily requires the use of a different amount of dispersion (i.e., physically changing the dispersive medium), so that the system is set for clock recovery by a fixed, prescribed rate division factor, and it cannot be easily tuned afterwards. In contrast to previously reported TSI-based clock recovery methods, the required dispersion is fixed in this method and the desired clock division factors is tuned only by changing the temporal phase modulation profile. Proof-of-concept experiments are demonstrated to verify the proposed

technique. In particular, we report successful clock extraction of 5.55-GHz, 2.22-GHz, and 1.11-GHz sub-harmonic clock signals as well as the 11.1-GHz base-rate clock signal from an 11.1-Gbit/s RZ-OOK binary on-off-keying (OOK) data signal.

4.2 Perspectives

I have proposed and experimentally demonstrated a novel method for programmable waveform intensity amplification without using active gain by recycling energy already stored in the input signal. In particular, our demonstrated technique represents an amplification method that can be potentially applied to repetitive signals in all wave systems, eliminate the wasted power inherent in applications aimed at peak power amplification, and it does not amplify or inject noise in the output signal.

Recently, it has been shown that Talbot amplification performs a process similar to conventional averaging, for example, scope averaging, on ASE-like intensity noise fluctuations in the input waveform train [18]. Following Talbot amplification by a gain factor of m , the repetitive waveforms undergo an intensity noise-mitigation process that is equivalent to averaging m consecutive waveforms. Said another way, Talbot amplification is equivalent to a scope averaging process without the need for detection and post-processing. Such a Talbot averaging process could be particularly important when a clean pulse is needed on the fly, e.g., directly in the optical domain. Moreover, in the case of scope averaging, the noise floor and waveform peak always average to their same respective levels, thereby the extinction ratio (ER) of the waveform train remains constant. Thanks to the noiseless characteristics of Talbot amplification, Talbot averaging additionally enhances the waveform train ER as the gain factor is increased [18].

Obviously, as for any averaging process, the capability of tuning the averaging factor is critical for practical applications. However, in previous designs [18], a different averaging factor necessarily requires the use of a different amount of dispersion (i.e., physically changing the dispersive medium), so that the system is set to implement an averaging process by a fixed, prescribed averaging factor, and it cannot be easily tuned afterwards.

As an interesting potential perspective for the work reported in this Thesis, by adopting our newly proposed scheme, it might be feasible to create a Talbot averaging system for repetitive waveforms with a programmable averaging factor, without changing the dispersive medium, i.e., where the specific amount of averaging -equivalent to the number of waveforms that are averaged in the train- can be tuned by suitably programming the temporal phase modulation

function. This could be achieved using similar strategies to those reported here for programmable Talbot amplification and SH-CR, e.g., by programming the electronic modulation function in an electro-optic phase modulator.

More generally, the flexible electronic control demonstrated in our work for Talbot amplification may help in moving forward this promising technique from a proof-of-concept academic work to one that may begin to be adopted for use in research labs or commercially.

PUBLICATIONS

Journals

- [J1] **J.Jeon**, R. Maram, J. Van Howe, and J. Azaña, "Programmable passive Talbot optical waveform amplification," *Opt. Exp.* **26** (6), 6872-6879, Mar. (2018).
- [J2] **J.Jeon**, R. Maram, J. Van Howe, and J. Azaña, "Programmable sub-harmonic clock recovery," *IEEE Photon. Technol. Lett.*, submitted (2018).
- [J3] R. Maram, M.Seghilani, **J. Jeon**, X-Z. Li, L. Romero Cortés, J. van Howe, and J. Azaña, "Demonstration of input-to-output gain and temporal noise mitigation in a Talbot amplifier," *IEEE Photon. Technol. Lett.* **30** (8), 665-668, Feb. (2018).

Conferences

- [C1] **J.Jeon**, R. Maram, J. Van Howe, and J. Azaña, "Programmable passive waveform amplifier based on temporal self-imaging effects," Conference on Lasers and Electro-Optics (CLEO), San Jose, USA, paper: SF2L.1 (2017).
- [C2] **J.Jeon**, R. Maram, J. Van Howe, and J. Azaña, "Programmable sub-harmonic clock recovery based on dispersion-induced inverse temporal self-imaging," Conference on Lasers and Electro-Optics (CLEO), San Jose, USA, paper: JTU2A.51 (2018).