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Vestigial Side Band (VSB) Modulation Formats for Ultra-high Capacity 40 Gb/s Optical Communications Systems

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VESTIGIAL SIDE BAND (VSB) MODULATION FORMATS FOR ULTRA-HIGH CAPACITY 40 Gb/s OPTICAL COMMUNICATIONS SYSTEMS

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1 Summary

During the last few years, the ever-increasing data traffic on every telecommunications network, even after the spectacular downfall, especially including the Internet, we have seen a unique explosion of intense research in order to increase channel capacity responding to the projected massive bandwidth demands in the near future. One such research effort is on 40 Gb/s per channel in optical Dense Wavelength Division Multiplexing (DWDM) communications systems. Furthermore in order to increase the information capacity that could be transmitted over a single fibres it is essential that the effective bandwidth of the transmitted signals is minimum, hence reducing the dispersion effects of the fibres and the suppression of the optical carriers to reduce the average optical power of all channels so as to increase the transmitted power below the non-linear induced dispersion level. Furthermore when several optical-carriered channels are multiplexed the average optical power of these channels is increased due to the optical power of the carriers, hence leading to the induced nonlinear dispersion effects. It is thus very necessary to suppress the optical carriers by generating in parallel a 180 degree phase shift channels so that the fibre would see the composite channel as a carrier suppressed channel. Therefore the Return-to-zero Double Side Band modulation has been developed for the purpose. In order to maximize the potential of the laid fiber, it is important to explore other advanced modulation schemes.

Vestigial Side Band Return to zero (VSB-RZ) and VSB-NRZ modulation formats are investigated in this report as they would exhibit narrow signal bandwidth and carrier suppression, in which the transmission passband is filtered to reject either the upper or lower side band. Hence the design of the optical filter for the generation of VSB is also described. Once the filter is realized, transmission simulation is conducted over long-haul single mod optical fibre communications systems.

Finally, comparison are made between NRZ-VSB to RZ VSB formats on their system tolerance of dispersion impairments and optical power levels using simulated eye closure and other factors.

2 Introduction

In the past few decades the need of higher bandwidth in networking systems has increased by many folds. This has been greatly due to the rapid acceptance of the Internet into many offices and homes, that is the fibre to the building (FTTB) and fibre to the home(FTTH). No one could have predicted the network growth necessary to meet this demand. Most providers are coping with fiber exhaust due to this explosion in consumer demands. An industry survey indicated in 1995, the amount of embedded fiber already in use in the average network was between 70 to 80 percent.

To fulfil these demands there has been a tremendous drive to increase the tchannel capacity by multiplexing several lightwaves channels, the Dense Wavelength Division Multiplexing (DWDM) at 40Gbps per channel. DWDM further allows us to pack even denser wavelength channels if the photonic technology is matured enough to provide appropriate multiplexers and demultiplexers..

We have reported the carrier-suppressed return-to-zero (RZ) and Non-RZ formats for extending the system impairment in linear dispersion and nonlinearly induced distortion[15]. However there are other more efficient modulation formats that may be considered to be more bandwidth efficient and more resilient to linear and nonlinear induced dispersions.

To incorporate this multiplexing technology into optical systems, the possibility of Return to Zero-Vestigial Side Band (RZ VSB) modulation to meet specified requirements is explored. The greater spectral efficiency of the format is its major attraction for the purposes of DWDM. The thesis describes the design of optical band pass filters that can effectively filter out the redundant side band, from the RZ Double Side Band signal produced at the output of the external modulator. WE then propagate the modulated signals over a length of standard single mode fibres from 50 Km to 5000 km to demonstrate the efficiency of the modulation format. However the VSB formats do suffer the effects of the mismatch of optical passband and the requirement of filtering of the sideband of the DSB signals. These effects are investigated and described in details.

This report is thus organised as follows: IN section 3 the transmitter module including the generation of the optical carrier and the external modulation techniques to generate either Carrier-suppressed DSB RZ or NRZ. The use of optical filters to eliminate one side band of the DSB RZ or DSB NRZ is given with detailed investigation and design of optical filter of Butterworth, elliptic or Chebychev are described. Furthermore the effects of the filter passband and cut-off band on the distortion of the signals are studied in sections 4,5. The propagation of these formatted signals through standard single mode optical fibres is conducted to prove its resilience to impairments due to linear dispersion and non-linear distortion.

3 Transmitter Module and Optical Modulating Techniques

3.1 Introduction

As mentioned earlier, the focus of the report is to model a long haul 40 Gb/s DWDM Optical Network. Most current installed optical networks operate at 10 Gb/s, therefore to upgrade these networks to 40 Gb/s it requires modification of the DWDM transmitter and receivers. This section covers the essential photonic components of the optical networks.

The foremost step in the design of the optical link is to decide how the incoming electrical signal can be converted into an optical stream of 1's and 0's. RZ format shows considerable performance advantages for example, compared to NRZ, it has higher peak power, higher SNR and lower bit rate Furthermore the RZ format offers better immunity to fiber related non-linear effects, polarization mode dispersion (PMD effects of multiplexed channels like Cross Phase Modulation (XPM). The modulation formats are described in details in section 2.

RZ-VSB is the resultant of passing the RZ DSB signals through a band pass optical filter which would then effectively suppress most of one of the side bands of the RZ signal. The VSB spectrum, as determine section 3 of this report, has smaller bandwidth and thus higher spectral efficiency.

Finally sub-section 4 introduces photonic components of the modelled system that have not been modelled in MOCSS-2 [15].

3.2 Optical transmitter

The role of the optical transmitter is to convert the incoming electrical signal into the corresponding optical output domain which is then propagated over the fiber link. This lightwaves generation sub-system consisting of the laser source and external modulator/modulators to generate 40Gbps-encoded signals, has been incorporated from the MOCSS-2 simulator[15]. It primarily consists of a laser source driven at a constant bias current to generate continuous lightwave which are then subjected to electrical envelop modulation by an ultra-broadband external electro-optic modulator. A Distributed Feedback (DFB) Laser is used as the continuous lightwaves source on the basis of its primary advantage of narrow line width and frequency stability. This allows the tuning to any particular wavelength carrier which satisfies the ITU-wavelength grid.. Thus the transmitter module generated from MOCSS-2 consists of the DFB laser as a laser source and a Mach Zehnder modulator as the external modulator

3.3 Optical Modulation Techniques

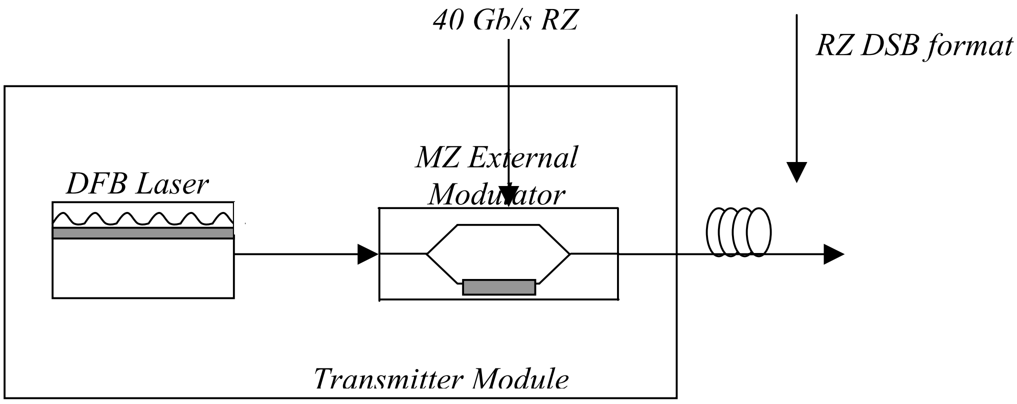

Figure 1: Transmitter module showing laser source and external modulator

3.3.1 Return–to–Zero (RZ) Modulation Format

Return to zero (RZ) and Non-Return to Zero (NRZ) are two choices available for the modulation of the incoming electrical signals; this thesis considers the RZ format. RZ format allows the bit coding with higher peak power, signal – to – noise ratio, and lower bit error rate compared to Non-return–to– zero (NRZ) coding. Other advantages include better immunity to fibre non-linear effects, polarization mode dispersion (PMD) and other non-linearities such as cross phase modulation (XPM).

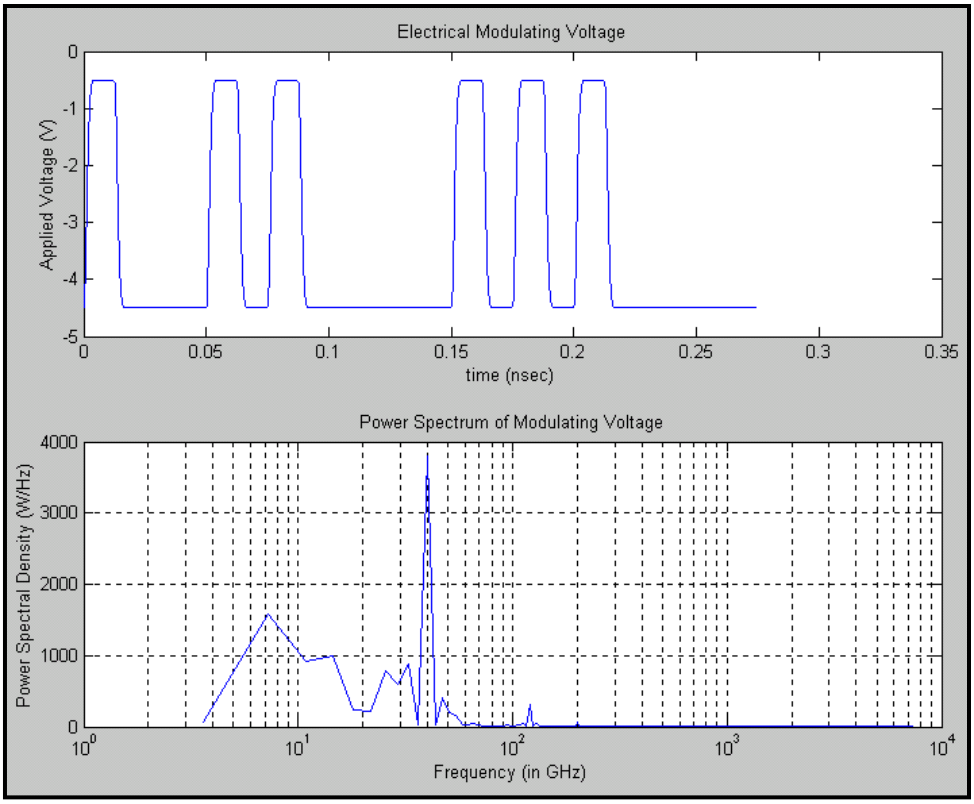

Figure 2 Signal spectra.

Return-to-zero (RZ) is a form of uni-polar encoding, which allows synchronization by having a signal change for each bit. Each pulse representing a ‘1’ is shorter than the bit slot, and its amplitude returns to zero before the bit duration is over. A high voltage represents a bit ‘1’ and a low represents a ‘0’. The upper half of *Figure 2* shows the applied voltage and the corresponding base band power spectral density (lower half of Figure 2); the modulating voltage is given by

$$V_m(t) = V_{off} + \sum_{n=0}^{N} b_n V_{on}(t - nT) \tag{1}$$

Figure 3 shows a bit stream 10110 coded using RZ; this is the format of the modulating voltage and that at the output of the external modulator discussed n the section hereafter. For the RZ VSB system modeled the code for RZ generation was incorporated from the MOCSS-2 system.

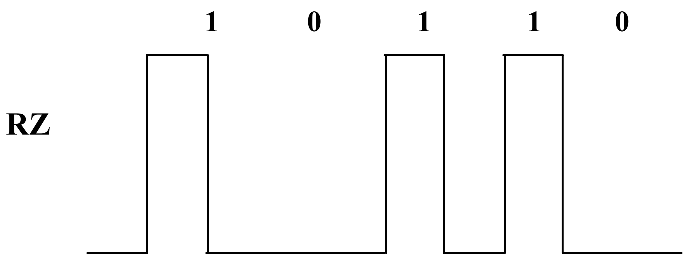

Figure 3: RZ coding of Bit Stream :10110

3.3.2 RZ Double Side Band Format – RZ DSB

The RZ modulated voltage is then applied to the traveling wave electrode of a MZ modulator. This generates in the RZ repetitive pulse trains as shown in the upper half of the Figure 4. It is seen that the signal follows the pulse shape of the modulating voltage. The power spectrum shown in the lower half of Figure 4 is obtained from the equation

$$E(t) = \sqrt{P_{out}(t)}\exp\left(j(\omega_c t + \phi)\right) \quad \textbf{(2)}$$

where $P_{out}(t)$ is the signal power, ω_c is the optical carrier frequency and Φ is the phase shift produced by the modulator. The optical power spectral density of a carrier modulated (zero shifted) RZ format signal of a 10-bit sequence; with a modulation index of 80% is shown in Figure 4. The spectrum is that of an amplitude-modulated system, normally referred as Double Side band (DSB) modulation-format signal.

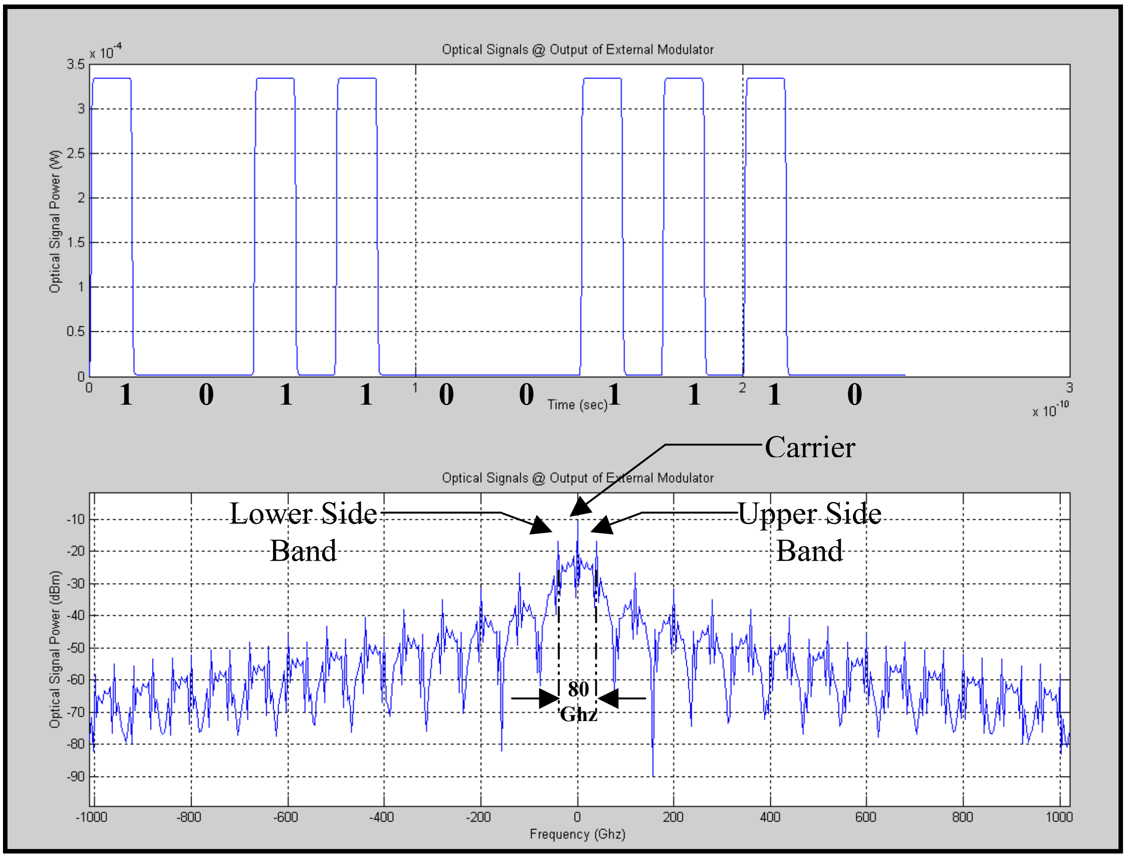

Figure 4 RZ Modulated Signal and Spectrum

To obtain the RZ VSB signal spectrum, it is required that either side band must be suppressed or filtered, this can be done by a band pass filter of 80GHz to filter out the unwanted component of the RZ DSB signal. The details of this mechanism will be discussed in the next section.

3.3.3 Return-to-Zero - Vestigial Side Band: RZ VSB

Although RZ-DSB shows high dispersion tolerance, immunity to non-linear effects etc, involves transmission of two side bands with exactly the same information. At high data rates up to 40 Gb/s and possibly higher to 160 Gb/s as considered in this report, the spectral efficiency is the primary factor and is considered as the key for next generation WDM optical transmission systems. Utilizing RZ-VSB modulation is essential to achieve high spectral efficiency as compared to that of RZ-DSB, by suppressing most but practically not all of the unwanted side band. In order to achieve this, an optical band pass filter is designed (as illustrated in the Appendix). Using a band pass optical filter, most of the lower side band can be suppressed leaving the carrier and the side upper side band. This is shown in Figure 5, where the bandwidth of the RZ DSB is 80 GHz as compared to the bandwidth 40Gh of the RZ VSB, by filtering out duplicated information carrying sideband.

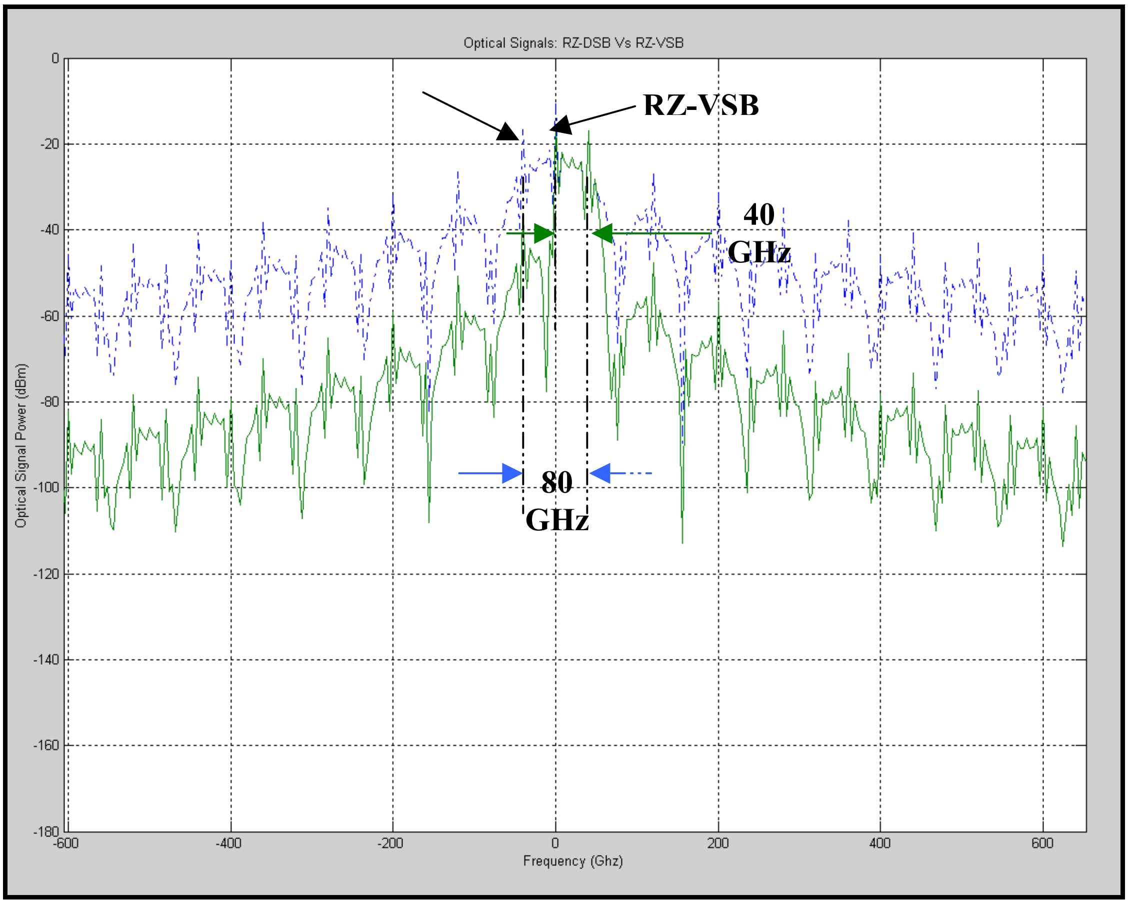

Figure 5: Optical spectra of RZ-DSB and RZ-VSB

The corresponding optical signal power plot for the two modulation formats is shown in Figure 6. The RZ VSB format, in the lower half of Figure 6, shows a Gaussian pulse shape after filtering; the narrow band property leads to its resilience to non-linear and dispersion effects.

The RZ-VSB can be obtained from the RZ-DSB signals passing through an elliptic-type optical filter. Design of this type of filter is presented in detail in Appendix A.

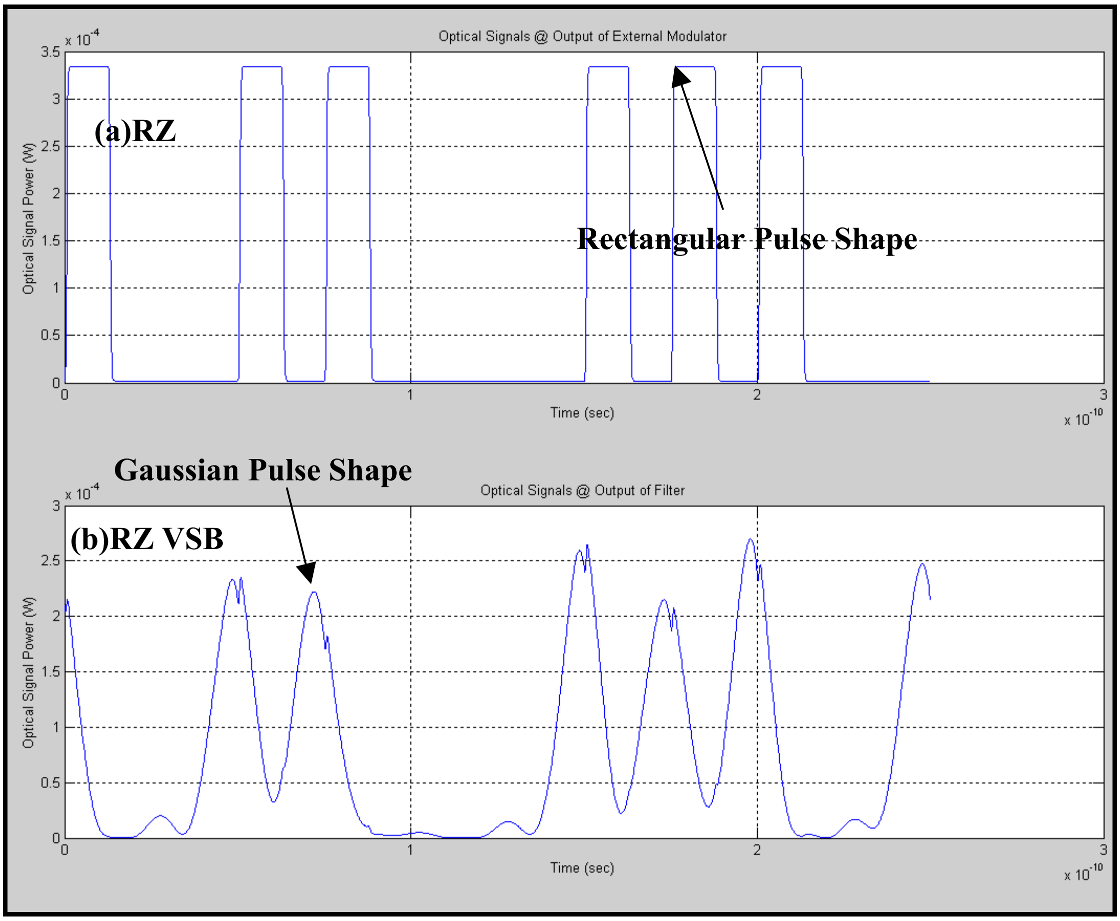

Figure 6: Optical Power Plots at (a) Output of External Modulator and (b) Output of Filter

3.4 Remarks

The RZ VSB format can be achieved by using an optical filter of bandwidth 80GHz. This filter cut-offs the lower side-band by at least 20dB in order to avoid signal distortion. The bandwidth of the signal is thus reduced from 80GHz in RZ-DSB to 40GHz in the RZ-VSB format. The stop band attenuation of the filter reduces the power of the unwanted side bands, thus reducing the interference of adjacent wavelength channels. The next section considers the requirement on the passband and cut-off band of an appropriate filter to effectively filter out most of the unwanted side band to generate the RZ-VSB.

4 Propagation of Modulated Optical Signals through the fibre channel

4.1 Introduction

Once the RZ-VSB signals are generated they are propagated through the fiber. A numerical method SSF (Split step Fourier) is developed for this propagation process including the effects of Loss, linear dispersion and other non-linear effects. The wave propagation through the fiber can be described by the Non-linear Schrödinger (NLS) wave equations and solved by employing the well known split step method.

4.2 Numerical Modelling

4.2.1 The Non-linear Schrödinger Wave Equations

. The wave equation that governs the propagation of light along silica fibers is given by:

$$\nabla^2 \tilde{E} + n^2(\omega)\frac{\omega^2}{c^2}\tilde{E} = 0 \qquad (3)$$

the propagation of lightwaves through non-linear and dispersive fibers can be obtained as.

$$\nabla^2 \tilde{E} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_o \frac{\partial^2 P_L}{\partial t^2} + \mu_o \frac{\partial^2 P_{NL}}{\partial t^2} \qquad (4)$$

where, P_L and P_{NL} are the linear and non-linear parts of the induced polarization $\left(P(r,t) = P_L(r,t) + P_{NL}(r,t)\right)$ are proportional to the electric field **E**(r,t).

Assuming that the spectral width of the light propagating through the fiber is very narrow, the fundamental guided mode is given as

$$j\frac{\partial A}{\partial z} + j\frac{\alpha}{2}A - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \gamma|A|^2 A = 0 \qquad (5)$$

where α is the attenuation coefficient, β the wave number and A(z,t) is the slowly varying envelope of the pulses propagating along the z direction.

The non-linear contribution at high powers can also be included and described by

$$n'_j = n_j + \bar{n}_2\left(P/A_{eff}\right), \qquad j=1,2 \qquad (6)$$

where n'_j with j=1,2 are the core and cladding refractive indices respectively and $\bar{n}_2$ is the non-linear index coefficient, typically of 3×10^{-20} m^2/W for silica based fibers. Thus the propagation constant becomes power dependent and can be written as

$$\beta' = \beta + \bar{\gamma} \cdot P, \qquad \text{where } \bar{\gamma} = {k_o \overline{n_2}} \Big/ {A_{eff}} \tag{7}$$

with the effective area A_{eff} depend on the spot size of the fibres. Therefore the non-linear effects that produce a non-linear phase shift can be expressed as

$$\phi_{NL} = \int_0^L \left(\beta' - \beta\right) dz = \int_0^L \bar{\gamma} \cdot P(z) \cdot dz = \bar{\gamma} \cdot P_{in} L_{eff} \tag{8}$$

where $L_{eff} = \dfrac{\left[1 - e^{-\alpha L}\right]}{\alpha}$ and for long fibers $L \approx \dfrac{1}{\alpha}$.

$P(z) = P_{in} \cdot \exp(-\alpha z)$ represents the fiber loss, where again the P_{in} is the average inpuit power of all multiplexed optical channels.

There exists a power dependence of the refractive index. In practical optical communications systems, P_{in} varies with time and hence causes a variation of refractive index as seen by the propagating wave in the fiber leads to distortion in the pulse shape, the Self Phase Modulation (SPM), which results in optical carrier chirping and spectral broadening of pulses propagating inside the fibers. Furthermore in DWDM system, we need to take into consideration the effect of Cross Phase Modulation (XPM). This can be considered as an extension of SPM where the non-linearity depends on the power of the channel on question but also the adjacent channels.

4.2.2 The Spilt-Step Fourier Method

Practically in an optical fiber, light wave experience both dispersion and non linear effects together. This method works by firstly assuming that each of dispersion and non-linear effects act independently on short spans of length h/2. Therefore, over the distance from z to z+h the non-linear effects can be taken to act from z +z(h/2) and dispersive methods from z+(h/2) to z+h. Therefore, the equation for partial derivative of A becomes

$$\frac{\partial A}{\partial z} = \left(\hat{D} + \hat{N}\right) A \tag{9}$$

where $\hat{D} = -\frac{j\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2}$, the linear dispersion propagation and attenuation *and* N is the non-linearly induced dispersion given by

$$\hat{N} = j\gamma\left(|A|^2 + \frac{j}{\omega_o}\frac{1}{A}\frac{\partial}{\partial T}\left(|A|^2 \cdot A\right) - T_R\frac{\partial |A|^2}{\partial T}\right), \qquad (10)$$

the propagation from z to z+h can be calculated by using the split step Fourier method using the approximation. The effect of non-linearity is included in the middle of the segment rather than to improve the accuracy of the method. That is,

$$A(z+h,T) \approx e^{\frac{h}{2}\hat{D}} \cdot e^{\int_z^{z+h} h\hat{N}(z')dz'} \cdot e^{\frac{h}{2}\hat{D}} \cdot A(z,T) \qquad (11)$$

Thus to implement this propagation the fiber is divided into segments of length h. the optical pulse propagating down through one segment follows two stages. First, the pulse is propagated a distance h/2 considering only its dispersion effects. Then at h/2, the non-linear effects occurring from z to z+h are taken are taken into account. The remainder of the length from z+h /2 to z+h considers dispersive effects again.

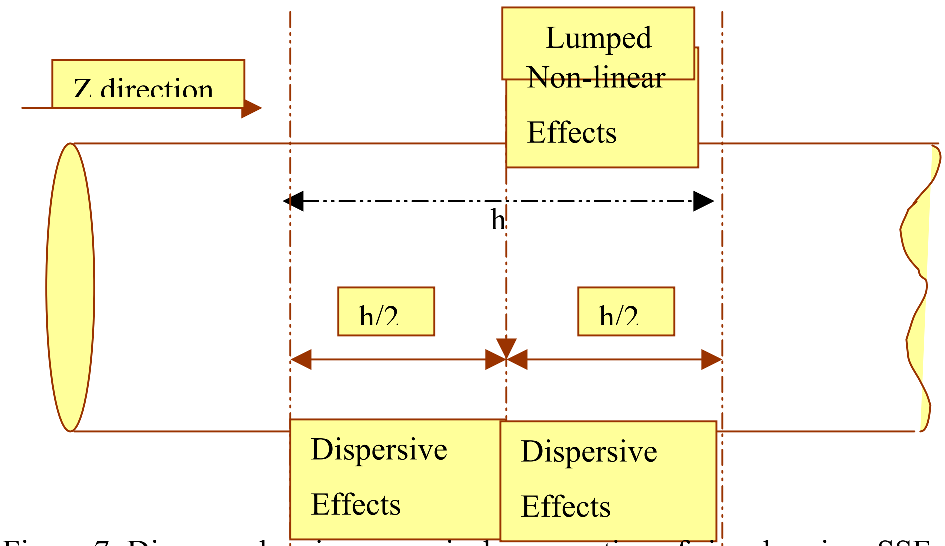

Figure 7: Diagram showing numerical propagation of signals using SSF Method

In effect the non-linear effects are lumped in the middle of each segment as shown in Figure 7. This method requires careful selection of step size h. one method to measure accuracy would be to calculate conserved quantities such as pulse energy, which must be conserved at every point along the optical transmission medium. The time window size should be wide enough to ensure the pulse energy is confined within this window. MOCSS-2 simulator uses the segment size, h=300m. One consideration taken into account in simulation using the fast Fourier transform is a circular convolution. To compensate for this, the mean of the two-signal level (not belonging to ‘0’ or ‘1’ – idle signal) is appended at either end.

The propagation method incorporated from the MOCSS-2 simulator has limitations and does not include certain non-linear effects in the split-step FFT analysis. These include the effects of Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Both arise due to the conversion of a high-energy photon to a lower energy photon, where the difference in energy appears in the form of a photon. The most critical difference between the two scattering effects is that, where SBS is caused by the scattering due to acoustic photons and SRS is caused by optical phonons (related to vibrations of the silica molecules). Four Wave Mixing (FWM) is another nonlinear effect not included in this simulation, this a major source of cross – talk in WDM light wave systems. This arises when 3 waves ($\omega_i,\omega_j,\omega_k$) co-propagating inside a fiber are spaced closely enough to satisfy the phase matching condition. This gives rise to a fourth wave $\omega_{F=}$ $\omega_{I+}\omega_{j-}\omega_{k.}$ This effect FWM increases with the number of channels in the multiplexed system, therefore in an N-multiplexed channel system with various combinations of i,,j,k from 1 to N can result in a large combination of new frequencies generated by FWM. Since our simulation does not include multiplexing as yet, the effect of FWM and SBS was ignored from the simulation.

Therefore, including the effects of dispersion, losses and non-linear effects of (GVD, SPM etc), the resulting signal spectra at the receiver end are as shown in the Figure 8. The pulse broadening seen in the upper half of Fig.8 suggests dispersion effects are active. The reduction of carrier and upper side band power indicates attenuation occurring on propagation.

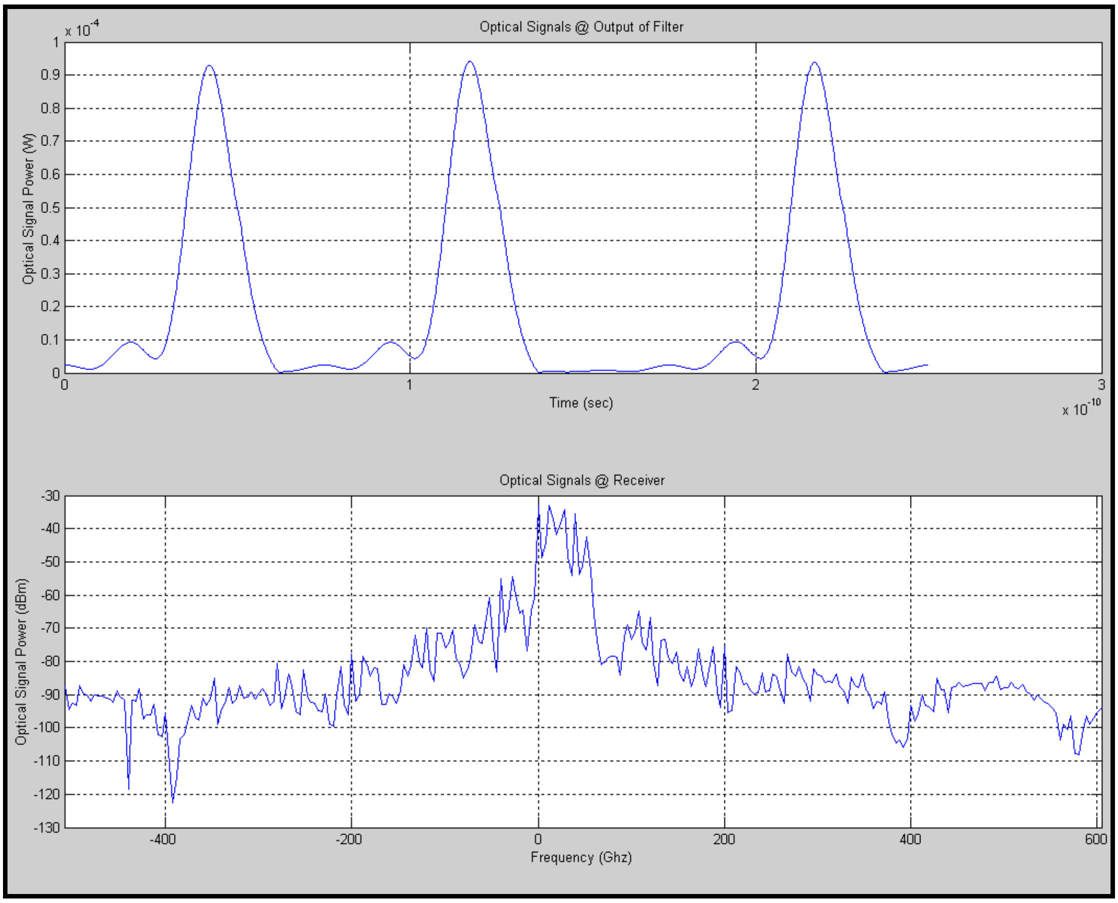

Figure 8 Optical Signal Power and Power Spectrum after 50 Km propagation through the simulated transmission link.

4.3 Remarks

This section further investigates the transmission link in the modeling of the optical link. The RZ-VSB signal passing through it incurs both dispersive and non-linear effects. The simulation of the transmission link was achieved by modeling the transmission medium by the non-linear Schrödinger (NLS) equation. The modeling has included only self phase modulation and not the other effects such as FWM , Cross Phase Modulation (XPM) and the scattering effects Stimulated Raman (SRS) and Stimulated Brillouin (SBS).

A comparative study between RZ VSB and RZ VSB will be given in the next section on the basis of power spectrum and eye diagram performance. The eye diagram for the RZ VSB is generated for transmission over 50 km Standard single mode fibre. The spectral efficiency and tolerance to dispersion of RZ VSB would be observed.

4.4 Concluding remarks on VSB-RZ formats

High spectral efficiency has been considered a key towards the next generation DWDM optical networks. This thesis has proved RZ-VSB as a successful candidate in the range of available modulation formats. It has shown resilience to dispersion and higher spectral bandwidth as compared to conventional RZ modulation.

A detailed design and analysis of three optical band pass filters. The Butterworth, Chebychev I and Elliptic Filters are outlined in the Appendix.

5 VSB-NRZ Modulation and Encoding Schemes

5.1 Introductory remarks

In previous section the VSB-RZ modulation format has been proven to be superior as compared with other conventional RZ, and CS-RZ .It has been also shown that CS-RZ format is an appropriate choice for 40Gbps optical long-haul communication system because of its robustness to dispersion tolerance and high nonlinearity tolerance compared to conventional RZ modulation format. This section focuses on the VSB format whose properties can provide higher spectral efficiency than double DSB CS-RZ modulation format, and also offers high tolerant to nonlinear effects.

5.2 Laser Source and VSB external optical modulator

The simulation of VSB CS-RZ and DSB CS-RZ modulation format are based the Monash Optical Communication System Simulator (MOCSS-2) package[15], where the transmitter sub-system comprises a laser source and an external modulator in order to be able to encode signals for up to 40Gbps.

A typical semiconductor laser such as DFB can only be directly modulated up to 10Gbps; since the simulation at 40Gbps an ultra-broadband external modulator is essential such as LiNbO3 travelling wave electro-optic interferometric intensity modulators or an electro-absorption modulator. The laser source is turned on continuously at a constant current and then its lightwaves output is modulated by the external modulator. Figure 9 shows a model of a transmitter used in simulation at the transmission rate of 40Gbps. For the generation of DSB CS-RZ signal, a second external modulator is needed for inducing a π phase shift on the other arm..

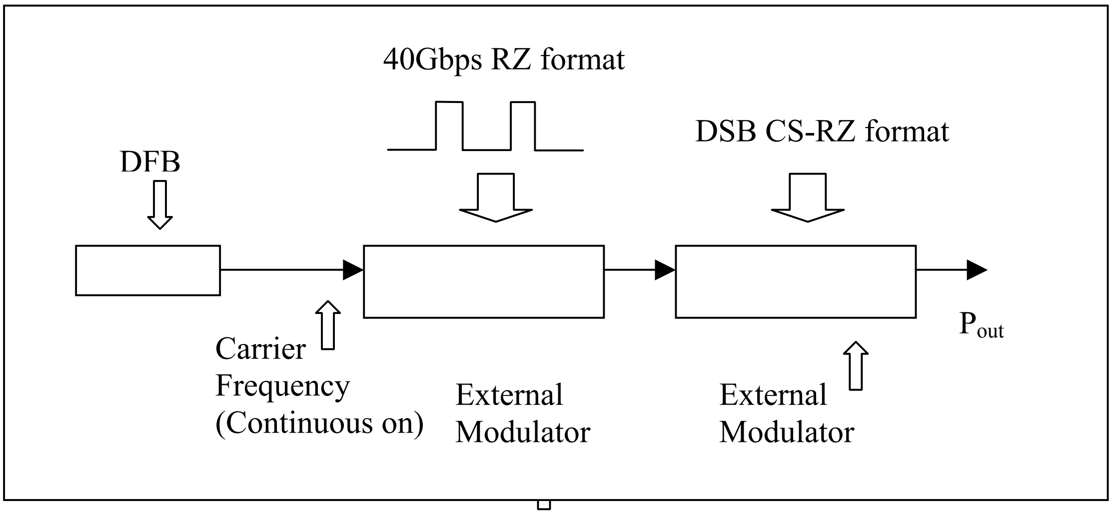

Figure 9: The Transmitter Mode.

The linewidth of the laser source which is a crucial issue in dispersion budgeting, plays an important role in determines the performance of a high-speed, long haul optical network, by determines the maximum transmission distance. DFB, which is tuneable to generate the required optical wavelength for the carrier has been selected as the laser source for the simulation works, since it is the appropriate choice for 40Gbps long haul communication systems because of its extremely narrow linewidth [1]. Hence the dispersion is due to mainly by the spectral width of the modulated signals.

5.2.1 Mach-Zehnder interferometric intensity optical Modulator

As mentioned before, CS-RZ employs external modulator to modulate the laser signal in order to obtain 40Gbps modulation rates and avoids spectral broadening due to the restrictions of directly modulated lasers. $LiNbO_3$ Mach-Zehnder optical intensity modulator which has a large mode field diameter and hence a good light confinement factor, small coupling lose and far better interaction speed with light than electronic components, has been selected as the transmitter module for the simulation, it is derived from the MOCSS-2 [1,15].

5.2.2 Optical Filters

DSB CS-RZ signals are modulated externally using the Mach-Zehnder modulator and being filtered out by the VSB bandpass filter before multiplexed onto the transmission channel in order to obtain the VSB CS-RZ signals.

VSB CS-RZ modulation formath involves filtering out most, but not all of the unwanted sideband from the DSB CS-RZ signal. Various digital filter designs such as

Butterworth, Chebyshev and Elliptic filter designs have been investigated and discussed in the Appendix.

There are two types of practical filters in the optical domain: they are dielectric multilayer filter and fibre-Bragg grating or micro-ring resonators. The structure of the optical filters are built based on the impulse response of the desired filter can be designed by using dielectric multi-layers of two types of materials with alternate high and low refractive indices. However, this is beyond our scope of this study.

5.2.3 Return-to-Zero Modulation Format

Conventional non-return-to-zero (NRZ) modulation formats have been used extensively in many data communication systems mainly because of its relative ease of generation and because of its signal bandwidth, which is only half of the RZ format. However, it is more adversely affected by nonlinearity effect, such as self-phase modulation (SPM) and cross-phase modulation (XPM). The distinct transitions between the RZ encoded bits produce a synchronous and clearer signal for the receiver to read. As a result, RZ modulation has become the more appropriate choice for terabits long haul optical communication systems, since it offers high dispersion tolerance and nonlinearity tolerance which lead to lower bit error rate (BER). Therefore, the thesis is focused on RZ format, since the area of investigating is for ultra-high speed, long haul systems. The performance of RZ format compare to other proposed modulation format will be described in detail later on in this report.

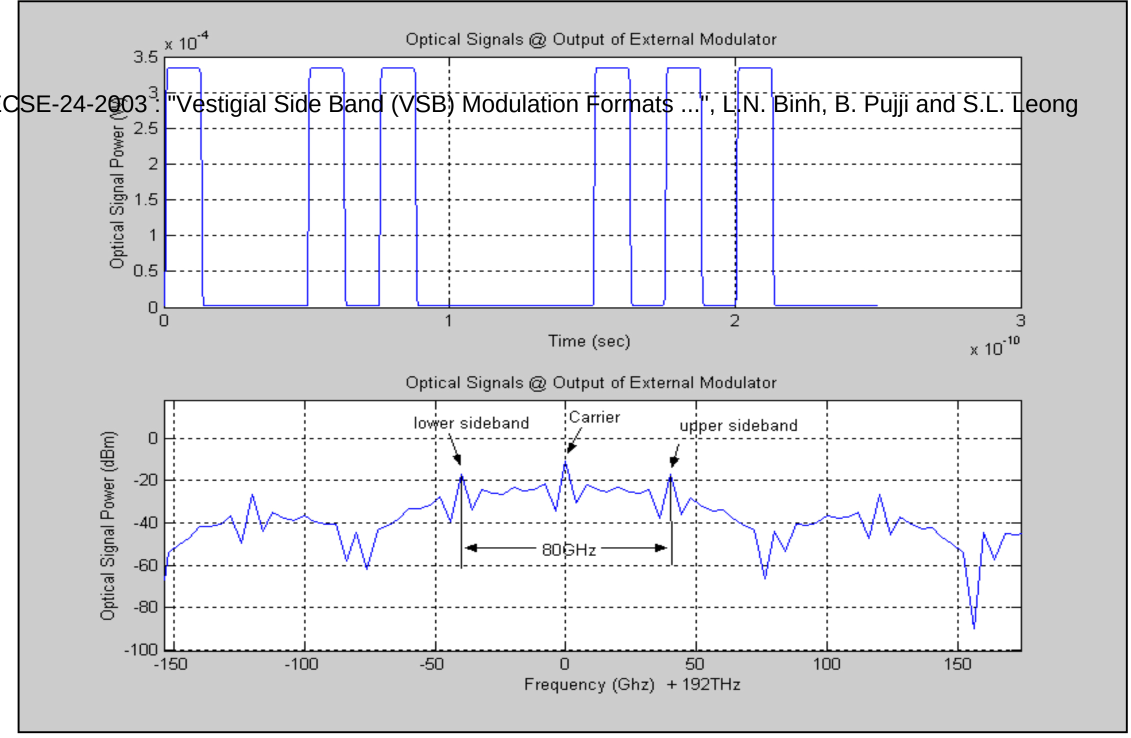

Figure 10 Optical signal power and corresponding power spectral density of 40Gps RZ format with a bandwidth of 80 GHz between the 2 sidebands

5.2.4 Double-Sideband Carrier-Suppressed Return-to-Zero Modulation Format

As mentioned above, the spectral efficiency and optical power margin are also very critical beside of optical signal-to-noise ratio, bit error rate and non-linear effects. DSB CS-RZ modulation format has been proposed to eliminate the spectral efficiency and high dispersion tolerance. Besides, power spectral density of RZ modulation as shown in Figure 10, comprises a carrier frequency, upper sideband and lower sideband. Most of the transmitted optical power resides in the carrier frequency, which contains no useful information that results in an inefficient system. Therefore, DSB CS-RZ modulation is an amplitude modulation with carrier-frequency component suppressed. The transmitter power as seen by the fibre is lower and an increase of the spectral efficiency can be implemented.

The transmitter module of the DSB CS-RZ modulation format comprises of a DFB laser source and 2 MZ-modulators. The DFB laser diode is generating the required-carrier lightwaves that then modulated by two push-pull type MZ intensity modulators. The first modulator is driven by a 40Gbps baseband signal and generates the 40Gbps RZ signal, while the second modulator is driven by a 20GHz sinusoidal clock signal biased at the transmission null point, V_{bias} so that the relative optical phase of the modulated signal takes the values 0 and π alternatively. Therefore, there are two output signals produced which are π phase shifted for each input signal. The relative phase different between adjacent pulses is kept at π, as the carrier component in output signal spectrum is suppressed and the spectral width between upper and lower sidebands is halved of RZ signal after the first modulator, which is only 40GHz.

The resulting DSB CS-RZ output signals become soliton-like bit stream in RZ format as shown in Figure 10. The soliton pulses are immune to fiber non-linearity effects, since the effects from group velocity dispersion (GVD) and self-phase modulation (SPM) have cancel out each other, where SPM imposes a chirp on the signal while GVD broadens the pulses during propagation. The performance of DSB CS-RZ format will be discussed in the next section.

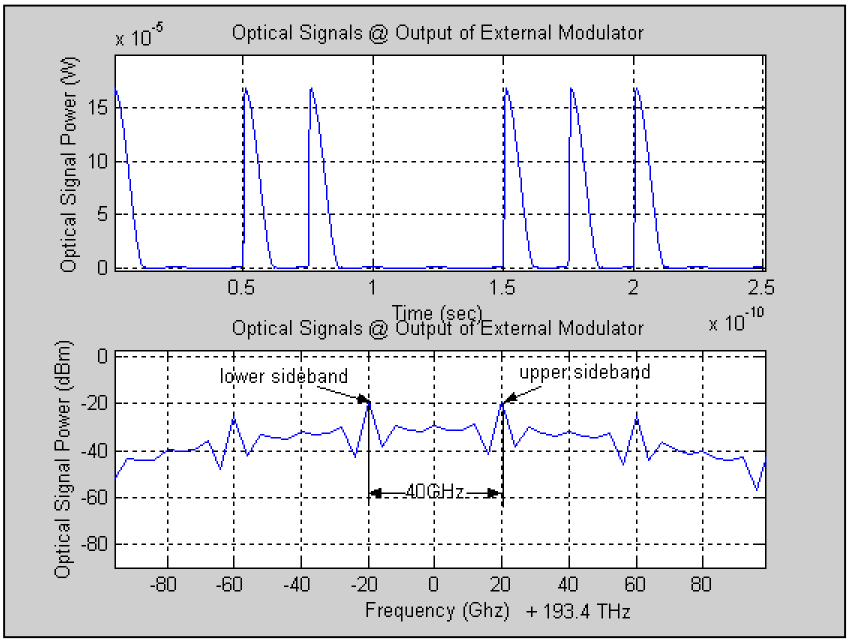

Figure 11 Optical signal power and corresponding power spectral density of 40Gps DSB CS-RZ format with a bandwidth of 40 GHz between 2 sidebands

As seen above, the carrier is clearly suppressed and the spectral width between the upper and lower sideband is half of the RZ signal, which is only 40 GHz.

5.2.5 Vestigial-Sideband Modulation Format

Although DSB CS-RZ has shown superior in optical power, dispersion tolerance, and immune to non-linear effects from the fibre; however, the information carried by both sidebands in DSB CS-RZ are exactly the same, and one of the band can be made redundant to increase the spectral efficiency. High spectral efficiency has been considered to be the key for the DWDM optical transmission system. The operation frequency of the optical filter assigned must be matched to the frequency region of the desired signal spectral. The penalty due to miss-matched of the optical filter and the signal power spectrum will be discussed later.

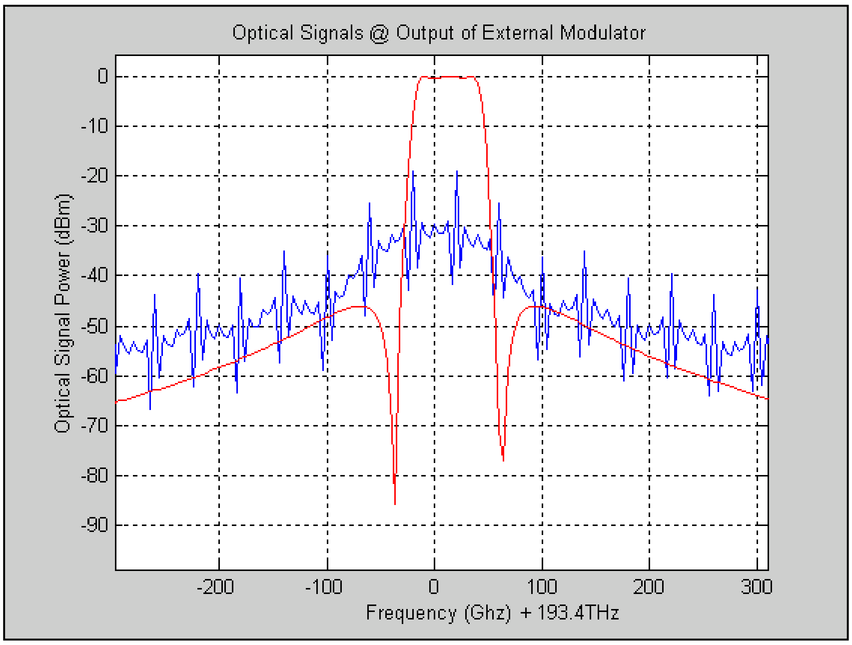

Figure 12 Optical signal power spectral density of 40Gps DSB CS-RZ format with a bandwidth of 40 GHz between 2 sidebands and the magnitude response of the elliptic filter with 50GHz passband bandwidth

6 Vestigial Side band-Non-Return- to-Zero

The possibility of Return to Zero-Vestigial Side Band (RZ VSB) modulation is explored in this section. The greater spectral efficiency of the format is its major attraction for the purposes of DWDM. As in previous sections optical band pass filter can effectively filter out the unwanted side band, from the RZ DSB signal produced at the output of the external modulator.

6.1 Transmitter Module and Optical Modulation Techniques

As mentioned earlier, the focus of this report is to model a long haul 40 Gbps DWDM optical transmission system. Most currently installed optical networks operate at 10 Gbps, therefore, to upgrade these systems it requires the modification of the transmitter and receiver systems. This section briefly outlines the essential photonic components for such systems.

The incoming electrical signal can be converted into an optical stream of 1's and 0's. RZ format shows considerable performance advantages for example, compared to

NRZ, it has higher peak power, higher SNR and lower bit rate. Due to transition to zero with each pulse there is an in built synchronization technique. Also, RZ offers better immunity to fiber related non-linear effects, Polarization Mode Dispersion (PMD effects of multiplexed channels like Cross Phase Modulation (XPM). The format is described in more detail in section 2 of this section.

RZ-VSB is the resultant of passing the RZ DSB signal through a band pass Optical Filter. The filter effectively suppresses most of one of the duplicate information carrying side bands of the RZ signal. The VSB spectrum, as shown in section 3 of this section, has smaller bandwidth and thus shows higher spectral efficiency and less subjective to linear chromatic dispersion. A detailed structure of the VSB transmitter is hsown in Appendix B and the design of optical filters is given in Appendix A.

6.2 The Optical transmitter

The role of the optical transmitter is to convert the incoming electrical signal into the corresponding optical output and then launch this optical input into the fiber. This generation segment, that is, the laser source and external modulator to generate 40Gbps-encoded signals, was incorporated from the MOCSS-2 simulator. It primarily consists of a laser source at constant current with a continuous wave output that has its high frequency carrier modulated by a high-speed external modulator. A Distributed Feedback (DFB) Laser is chosen as the continuous wave laser on basis of its primary advantage of narrow line width of 0.2nm and frequency stability. This allows the tuning to any particular wavelength carrier , these lightwaves channels must satisfy the allocations as determined by the ITU grid. Thus the transmitter module generated from MOCSS-2 consists of the DFB laser as a laser source and Mach Zehnder Modulator as the external modulator. Documentation is already covered in previous thesis and thus will not be repeated here.

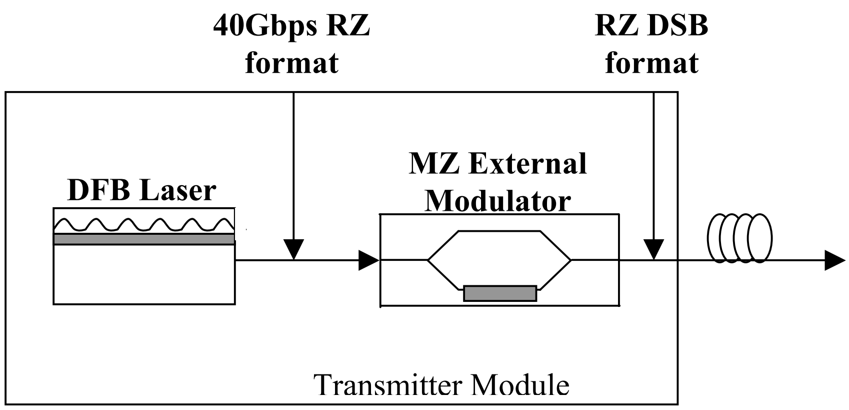

Figure13: Transmitter module showing laser source and external modulator

6.2.1 Return–to–Zero (RZ) modulators

Return to zero (RZ) and Non-Return to Zero (NRZ) are two choices available for the modulation of the incoming electrical signals; this thesis considers the RZ format. RZ format allows the bit coding with higher peak power, signal – to – noise ratio, and lower bit error rate compared to Non-return – to – zero (NRZ) coding. Other advantages include better immunity to fibre non-linear effects, polarization mode dispersion (PMD) and other non-linearities such as cross phase modulation (XPM).

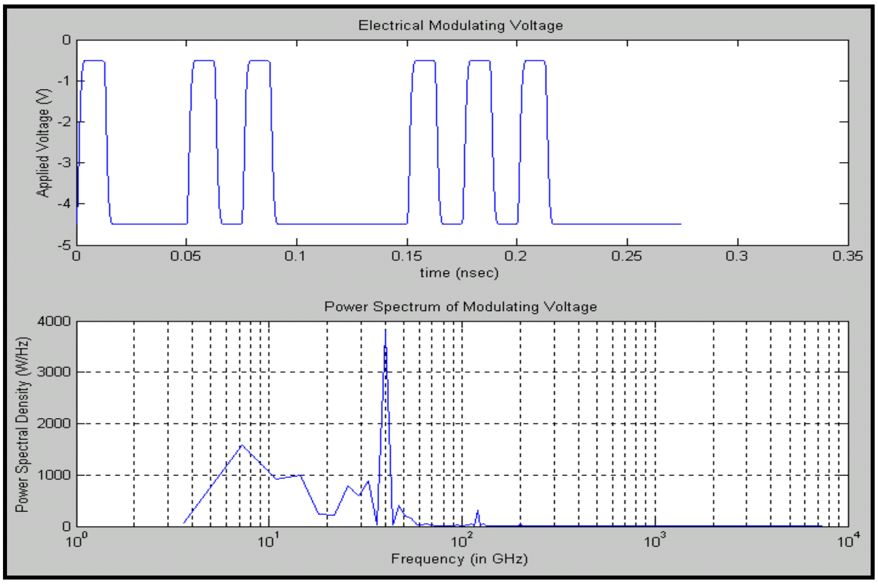

Figure 13 Coded pulse sequence as input voltage applied to the traveling wave electrode of the MZIM

RZ is a form of uni-polar encoding, which allows synchronization by having a signal change for each bit. Each pulse representing a '1' is shorter than the bit slot, and its amplitude returns to zero before the bit duration is over. A high voltage represents a bit '1' and a low represents a '0'. The base band power spectral density (lower half of figure 13), The modulating voltage is given by

$$V_m(t) = V_{off} + \sum_{n=0}^{N} b_n V_{on}(t - nT) \tag{11}$$

6.2.2 Return-to-Zero -Double Side Band –RZ DSB

The RZ modulated voltage is applied to the traveling wave electrode of the MZIM to modulate the amplitude of the lightwaves that is biased at the minimum transmission point of the optical power–electrode voltage transfer characteristics. This results in the return to zero signal pulse shown in the upper half of Fig. 14. It is seen that the signal follows the pulse shape of the modulating voltage. The power spectrum shown in the lower half of Figure 14 is obtained from the equation

$$E(t) = \sqrt{P_{out}(t)}\exp\left(j(\omega_c t + \phi)\right) \qquad (12)$$

where $P_{out}(t)$ is the signal power, ω_c is the optical carrier frequency and Φ is the phase shift produced by modulator. The optical power spectral density of a carrier modulated (zero shifted) RZ format signal of a 10-bit sequence; with a modulation index of 80% is shown in Figure 14 below. The spectrum is that of an amplitude-modulated system, otherwise referred to as Double Side band (DSB) modulated signal.

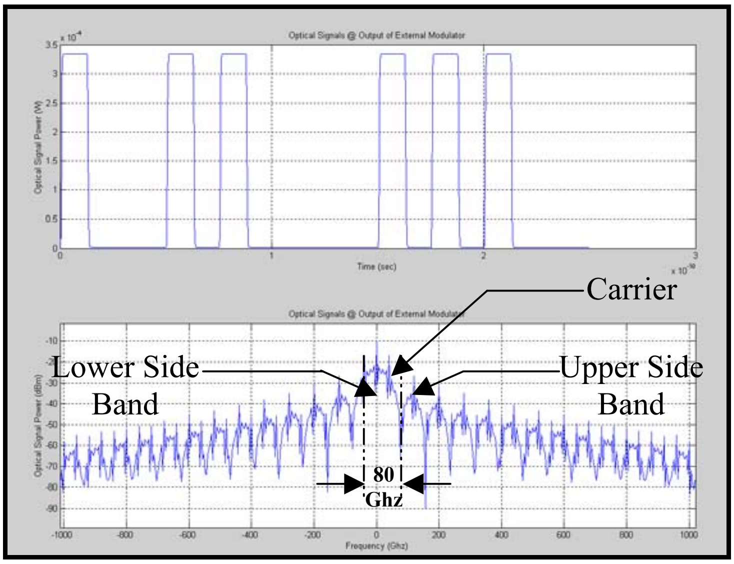

Figure 14: RZ Modulated Signal and Spectrum

To obtain the RZ VSB signal spectrum, it was required that partial suppression of either side band occur, this is implemented by inserting a band pass filter of 80GHz following the optical modulator to filter out the unwanted band and the optical carrier of the RZ DSB signal. The details of this filtering is discussed in the next section.

6.2.3 Return to Zero - Vestigial Side Band: RZ VSB

Although RZ-DSB shows high dispersion tolerance, immunity to non-linear effects etc, involves transmission of two side bands with exactly the same information. At high data rates as high as one considered in the thesis (40 Gb/s), spectral efficiency is primary factor and is considered the key for next generation WDM optical transmission systems. Utilizing RZ-VSB modulating is an attempt in achieving high spectral efficiency in comparison to RZ-DSB, by suppressing most not all of the unwanted side band. In order to achieve this, an optical band pass filter is designed (illustrated in the Appendix). Using a band pass optical filter, most of the lower side band can be suppressed leaving the carrier and the side upper side band. This is shown in Figure 15, where the bandwidth of the RZ DSB is 80 GHz as compared to the bandwidth 40Gh of the RZ VSB, by filtering out duplicated information carrying sideband.

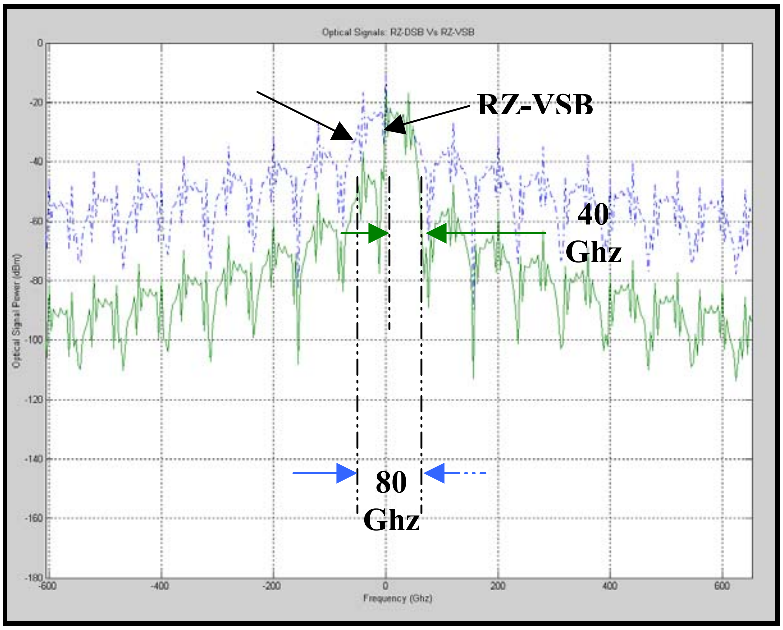

Figure 15: RZ DSB Vs RZ VSB

The corresponding optical signal power plot for the two modulation formats is shown in Figure 16. The RZ VSB format, as shown in the lower half of Figure 16, shows a Gaussian pulse shape after filtering indicating that it is resilient to non-linear effects.

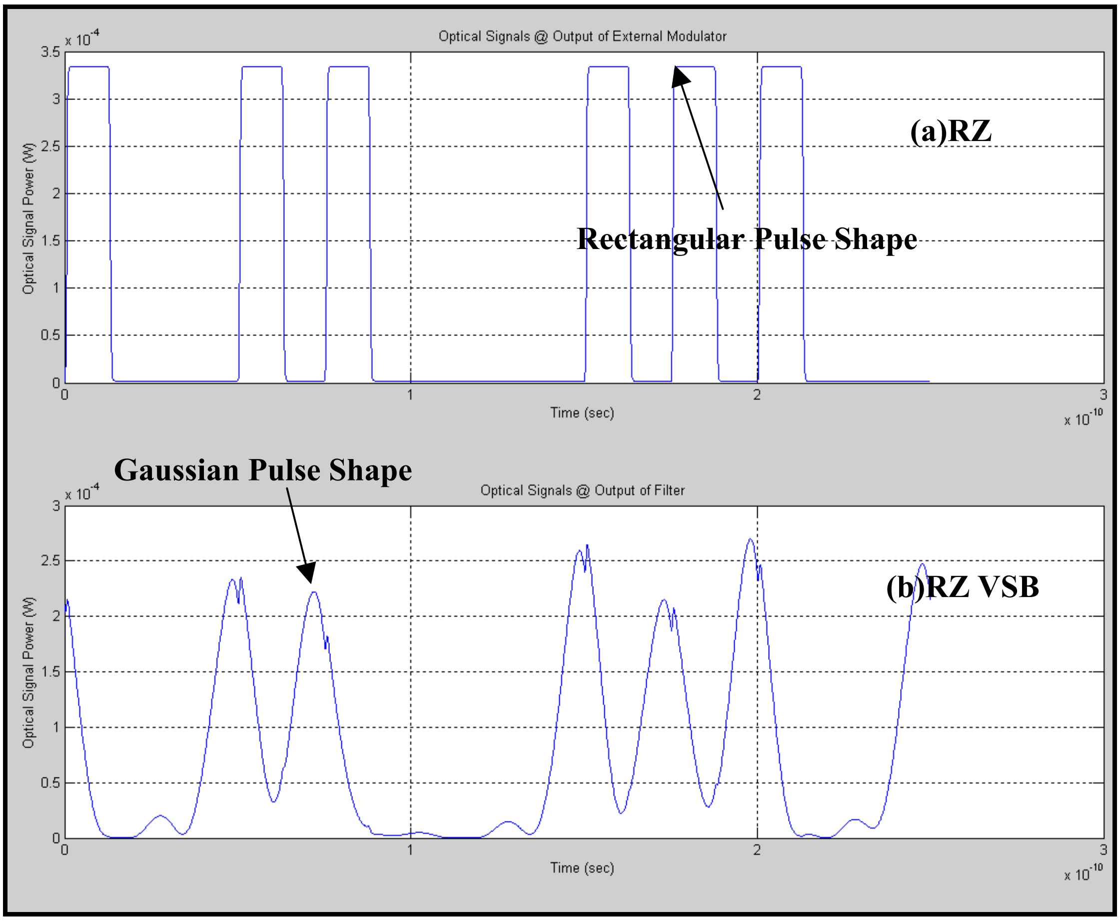

Figure16: Optical Power Plots at (a) Output of External Modulator and (b) Output of Filter

The RZ-VSB is obtained by passing the RZ-DSB through an elliptic type optical filter whose design has been outlined in details in the Appendix.

6.3 Remarks

It is now possible to generate the RZ-VSB modulation format. The RZ modulation format has been demonstrated. The RZ-VSB could be achieved by using an MZ modulator. The RZ-VSB format is then obtained by placing an optical filter after the MZIM of a bandwidth of 80GHz. This filter suppresses the lower side band more than 20dB. The bandwidth of the signal is reduced from 80 GHz in RZ-DSB to 40 GHz in RZ VSB format. The stop band attenuation of the filter reduces the power of the unwanted side bands, thus reducing the interference of adjacent wavelength channels. The next section further investigates an appropriate filter to effectively filter out most of the unwanted side band to generate the RZ-VSB.

7 Propagation of Optical Signals through the fibre

7.1 Introduction

Once the RZ-VSB or CS-RZ VSB was generated these signals are then propagated through the fiber spans. A propagation method is essential to propagate these optical sigansl subjected to the effects of loss, linear dispersion and other non-linear effects. The fiber Non-linear Schrödinger (NLS) wave equations (derived from Maxwell's equations) can be formulated and the Split step Fourier method (SSF) as outlined in Section 4 is used.

8 Comparison Between RZ-DSB and RZ-VSB

Both RZ-DSB and RZ-VSB have been simulated in previous sections. The figures above have shown the effects of dispersion and non-linear effects of SPM on the RZ VSB signal, after propagation through the fiber. The propagation was modelled using the NLS and solved using the split step method.

In order to determine whether or not the developed RZ-VSB modulation format is as effective modulation format as compared to RZ-DSB this section deals with comparing the tolerance of the formats to effects of dispersion and non-linear effects separately. The power improvement of the optical transmission link is also examined. Finally, the eye opening and closure can be used to evaluate for both modulation formats using the standard Q-factor versus the BER as shown in Figure 18.

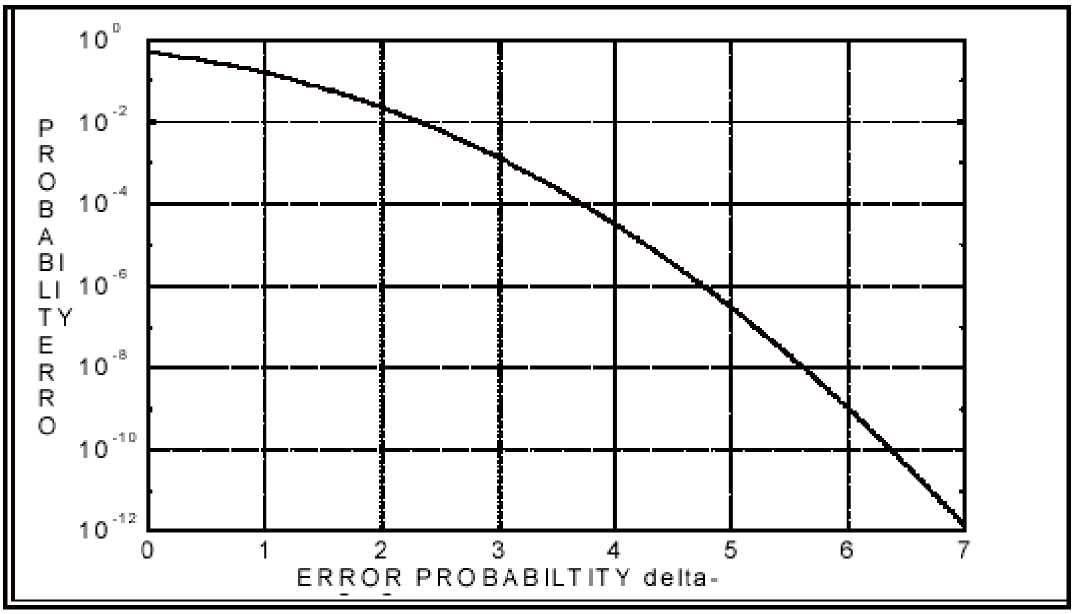

Figure 18: BER as a function of δ parameter.

The pulse signal and the power spectrum of RZ DSB are shown in figure 19

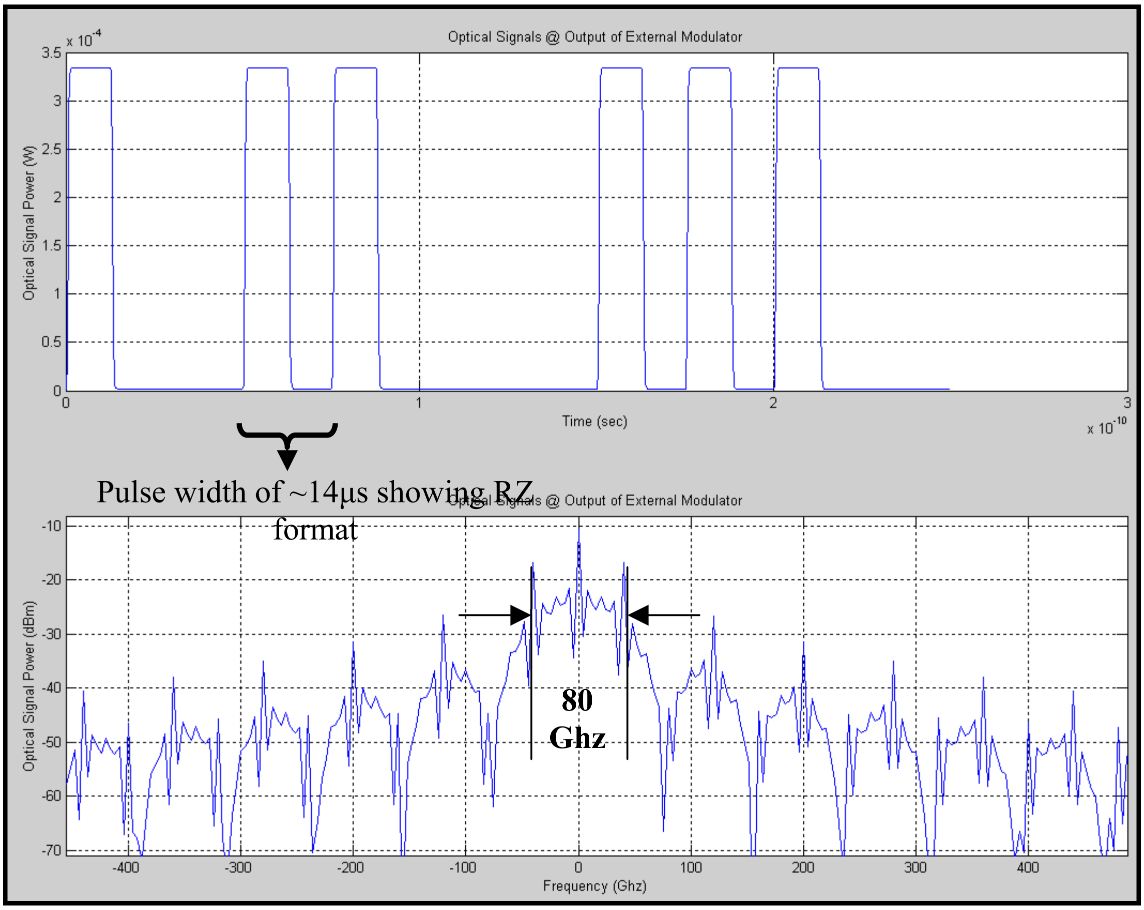

Figure 19: RZ DSB Pulse Signal power and power spectrum plots.

A pulse width of approximately 14ps with a repetition rate of 40 pulses can be generated for RZ DSB signals as shown in the upper half of Figure 19. It is also evident that return to zero format was used to encode electrical signals to bit stream of '1's and '0's. The lower half of Figure 19 shows the power spectrum of bandwidth 80 GHz. This is important to note when comparing with RZ VSB. The side bands carry a power of approximately -17dBW or about 20mW. The carrier power is estimated to be –10.7dBW or 85mW. The upper and lower side bands each carry the same information. These factors become important for comparison purpose.

The optical band pass filter designed has been described in earlier sections and the RZ VSB format is obtained from the RZ DSB by a convolution in the frequency domain. This is represented as a figure below.

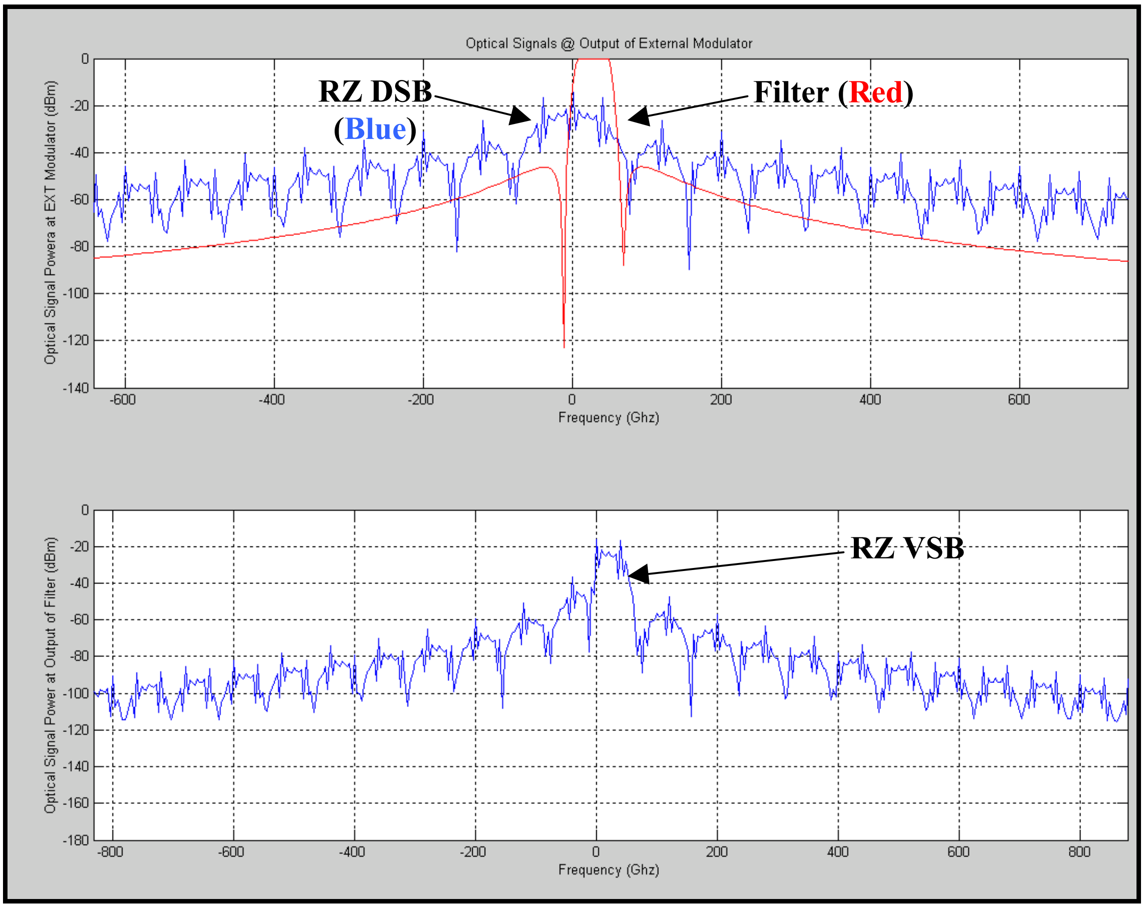

Figure 20: Plots of Signal power before and after filtering

It is also observed that there is a bandwidth reduction in the power spectrum. The signal power and power spectra of the two formats are shown in Figure 20. The power spectrum shown in the lower half of Figure 20 shows the bandwidth reduction to 40Ghz. The suppressed side band has power of –40dB (0.1mW), a reduction of 20 dB or 19.9mW reduction. Further, the unwanted side bands are further suppressed. The carrier power also shows a reduction at –15dBW or 31.5mW, for the RZ VSB. Further, the pulse signal power, exhibits a Gaussian shape, this shows the pulse will be less susceptible to dispersive effects along the fiber.

The RZ VSB signal power plots at the receiver end after transmission over 50 km of DCF are shown in Figure 21.

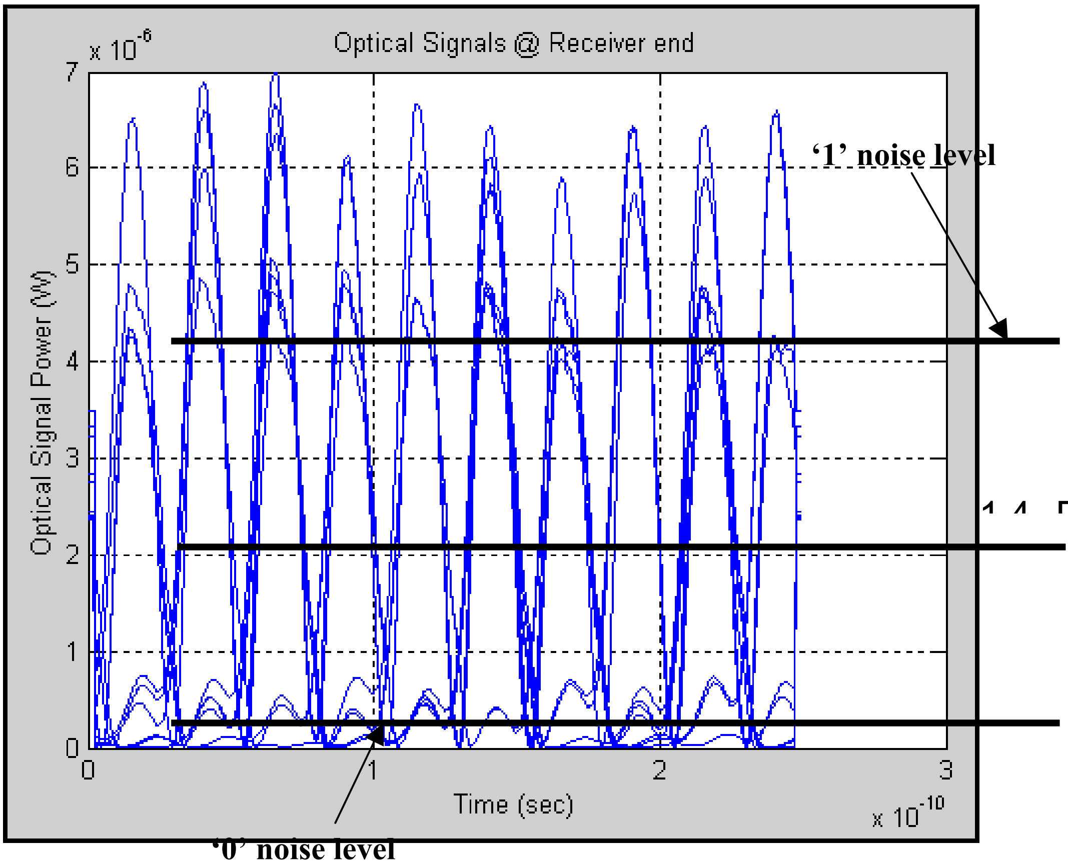

Figure 21: Eye diagram after transmission over 50Km

With reference to figure 4.4, the bit '1' noise level is estimated at 4.6. The bit '0' noise level at 0.7. The Q-factor can be estimated as Q= (2.3)/(0.35)=6.6 from figure 21 and the BER is approximately about $10^{-11.}$ This is the upper limit of BER for long haul optical links. Thus the RZ-VSB is an acceptable modulation format for 40Gbps long haul optical networks showing marginal BER. Higher spectral efficiency can be achieved by use of RZ coding techniques. Alternatively, bandwidth reduced formats like VSB can also be considered, as it has proven to demonstrate high spectral efficiency.

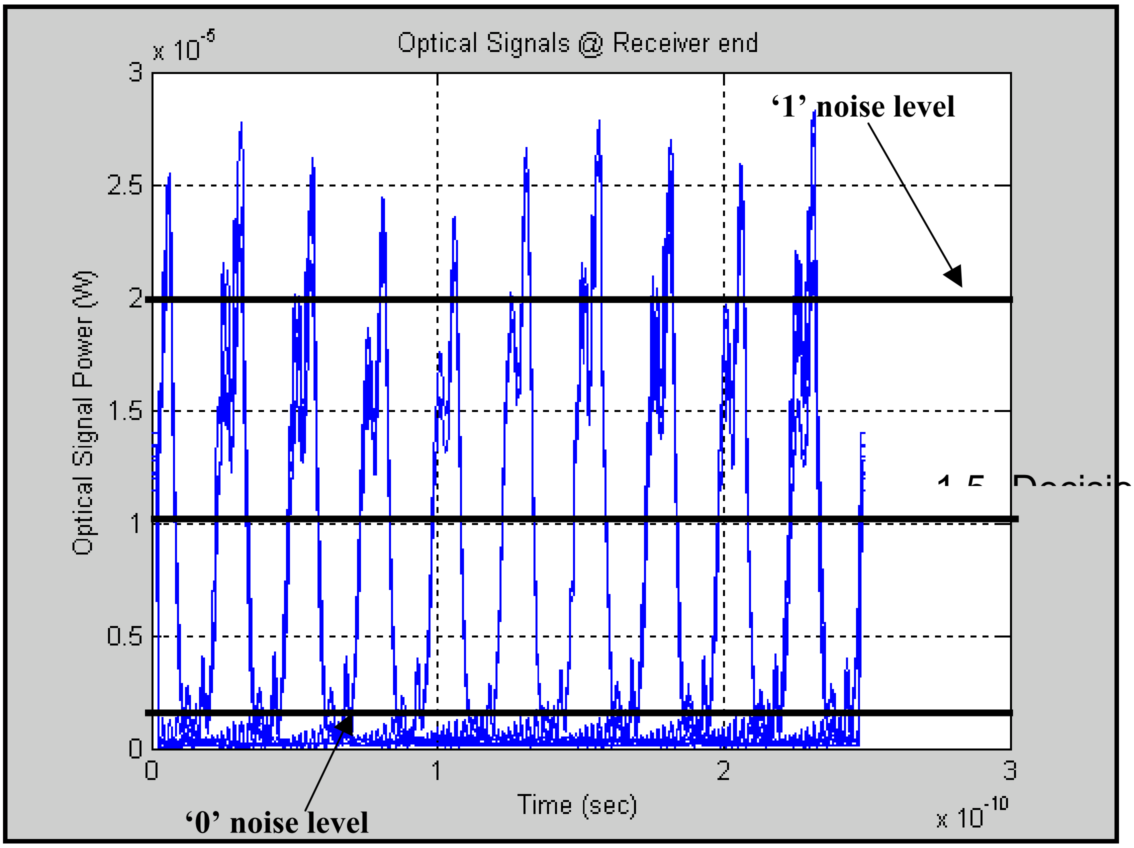

Figure 22: Eye diagram after transmission over 50Km

With reference to Figure 22, the bit '1' noise level is estimated at 2. The bit '0' noise level at 0.2. The δ can be calculated as Q = (1)/(0.2)= 5 and the BER can be estimated to be about 10^{-8}.Thus the RZ DSB has shown a higher BER for the same transmission link conditions.

Furthermore we increase the testing of the two formats over a transmission distance of the link 500 Km so as to compare with those obtained from the 50 Km above. The optical signal power and the power spectrum after 500 km are shown in the upper and lower halves of Figure 22 respectively.

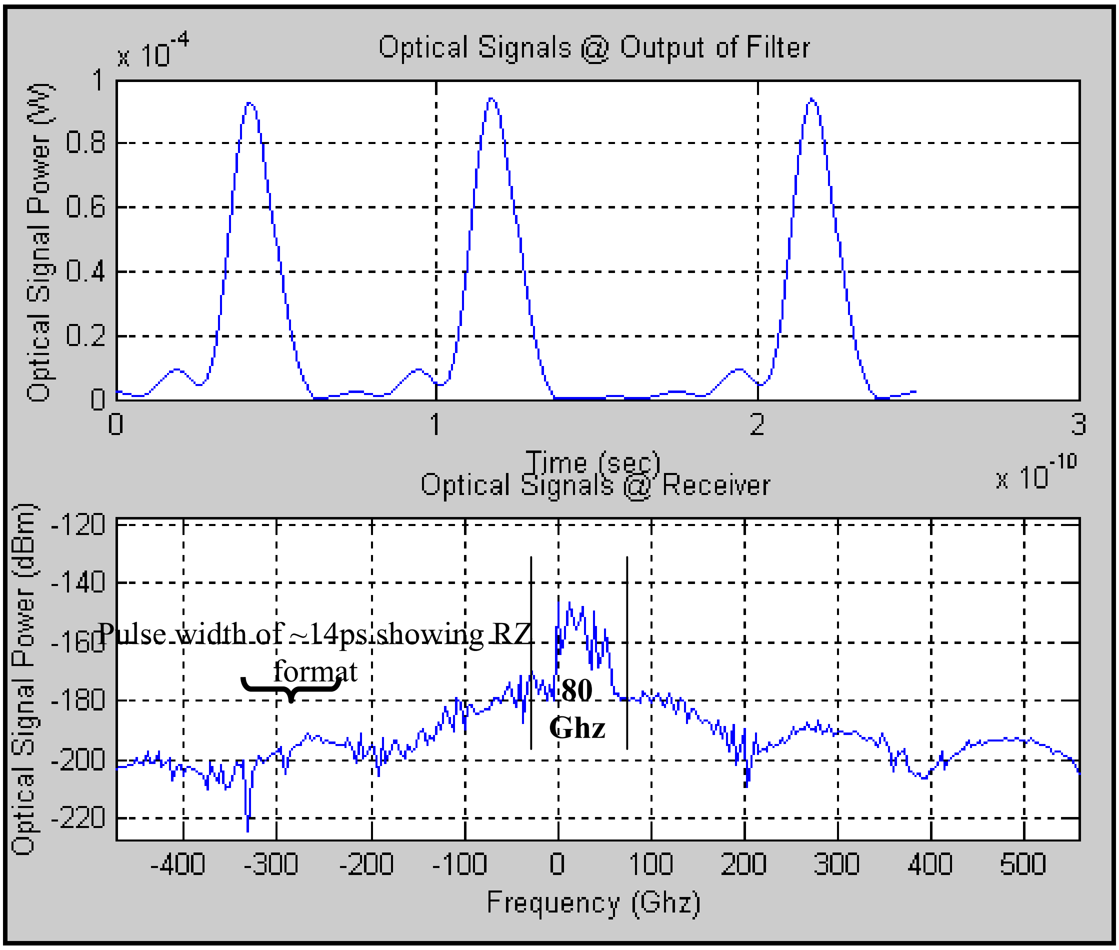

Figure 22: Optical Signal Power and Power Spectrum after 500 km transmission

The input bit stream for this simulation is 0 0 1 0 0 1 0 0 0 1. The pulse broadening shows dispersive effects in action. The figure above shows that the bit stream is still recoverable; also the VSB signal integrity is still maintained after 500 km with the carrier and the side band distinctly identifiable. This implies that the signal is highly tolerable to dispersion effects, and thus its suitability to long haul optical networks proved.

8.1 Concluding remarks

High spectral efficiency has been considered a key towards the next generation DWDM optical networks. This thesis has proved RZ-VSB as a successful candidate in the range of available modulation formats. It has shown resilience to dispersion and higher spectral bandwidth as compared to conventional RZ modulation.

A detailed design and analysis of three optical band pass filters, which could suit the application was carried out. The Butterworth, Chebychev and Elliptic Filters were designed. The elliptic filter was chosen based on it sharper roll off and stability in optical frequency applications.

8.2 Signal Characteristics of VSB CS-RZ Compared to DSB CS-RZ Modulated at 40Gbps

Spectral bandwidth of the signal is the prominent issue for WDM and DWDM systems since it is decisive for the channel spacing, where the ITU standard is 100GHz and 50GHz respectively. Figure 23 shows the optical signal spectrum of the DSB CS-RZ and VSB CS-RZ modulated lightwave. A way to determine the signal bandwidth is to measure at the 30dB-down from the peak power amplitude. For DSB CS-RZ, the $BW_{30dB\text{-}down}$ is approximately 200GHz while it is only 78GHz for VSB CS-RZ. The unwanted frequency components are filtered 20dB down in the VSB CS-RZ that reduce the signal bandwidth; and hence prevent the spectral crosstalk between the adjacent WDM or DWDM channels, or else the channel spacing can be reduced.

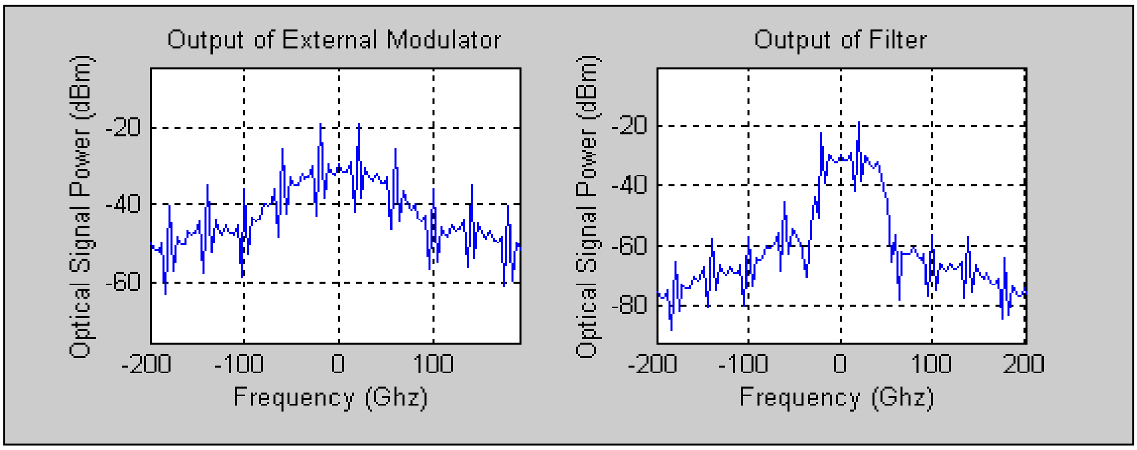

Figure 23 Optical Signal Spectrum of (a) DSB CS-RZ (b) VSB CS-RZ signal modulated at 40Gbps

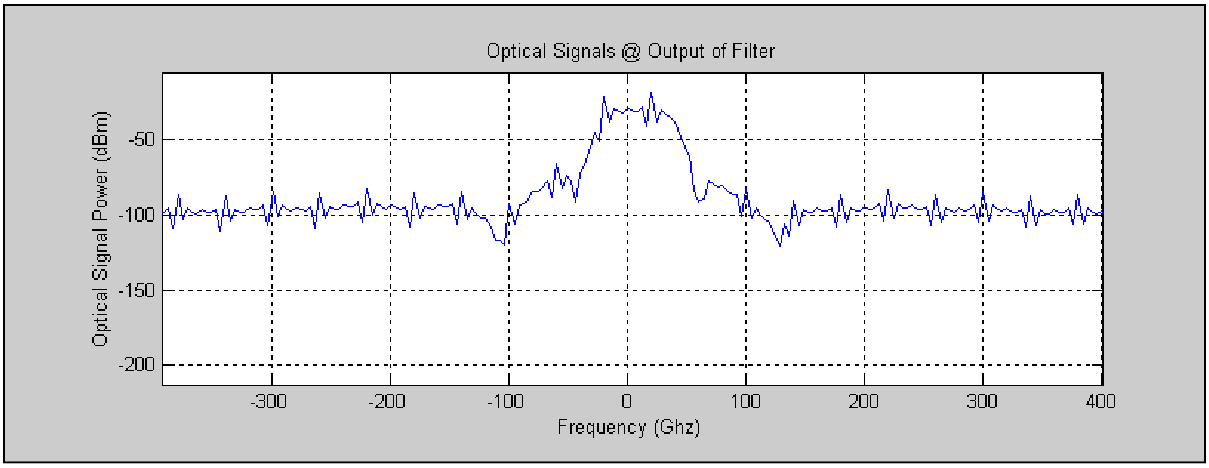

Figure 24 Optical Signal Spectrum of VSB CS-RZ signal modulated at 40Gbps (unwanted components been filtered 40dB down)

Figure 24 shows the VSB CS-RZ signal spectrum which involving attenuation of 40dB on the unwanted components; hence obtain the $BW_{30dB\text{-}down}$ of approximately 60GHz.

8.3 Remarks

In summary, the VSB CS-RZ modulation format has been introduced by inserting an optical filter at the output of DSB CS-RZ modulation module that comprises two cascaded Mach-Zehnder modulators after a DFB laser diode. The simulation has been conducted with care of most of the practical limitations in real system. The $BW_{30dB\text{-}down}$ of the signal has been reduced from 200GHz in DSB CS-RZ to 78GHz or even lower in VSB CS-RZ, which can significantly reduce the channel spacing and eliminate the spectral crosstalk. The spectral efficiency of the VSB CS-RZ is still remaining to be optimised by adjusting the filter configurations such as, roll-off, attenuation and etc.

9 Filtering Effects

The section verifies the effects of filtering, and hence the importance of the design of the filters which including the designs of passband ripple, stopband attenuation, operation frequency and roll-off region. Although both upper and lower sidebands of the DSB CS-RZ contain the same signal information. However when the filtering is removing all the unwanted sidebands it may lead to problems of faithfully recovering the signal pulse sequence, and hence the degradation of the signal to noise ratio(SNR) Therefore, VSB CS-RZ is preferable rather than SSB CS-RZ, where one of the sideband is totally filtered out although it offers smaller bandwidth. The mismatch of the filter passband region and the desired or wanted frequency components may also cause the problem of obtaining SSB instead of VSB, and this must be taken care in order to optimise the performance of VSB CS-RZ modulation format.

9.1 Effects of Filter Pass-band Ripple

The steepness of the roll-off region is depended on the passband ripple. As mentioned in last section, the equal-ripple in the passband allows the amplitude response to have a steeper rolloff outside the passband for a fixed filter order. Therefore, the optical filter with same passband bandwidth but with larger passband or stopband ripple will have a steeper roll-off and resulting in filtered off more unwanted components.

Figure 25 shows the optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from filtering of DSB CS-RZ by elliptic filter with the same centre frequency, same passband bandwidth of 50GHz, same attenuation of 20dB and different ripples of 0.1dB and 0.5dB respectively. The VSB CS-RZ obtained from the elliptic filter with 0.5dB passband ripples clearly have a narrower $BW_{30dB\text{-}down}$, hence lower sideband spectral has been filtered out. This results in optical pulses that are not ‘completely’ RZ format. This problem can be solved by shifting the centre frequency of the filter in order to not to obtain a maximum of 3dB down at either lower or upper sideband, so that the pulse signals wont significantly affected by the noise level, refer to Figure 26.

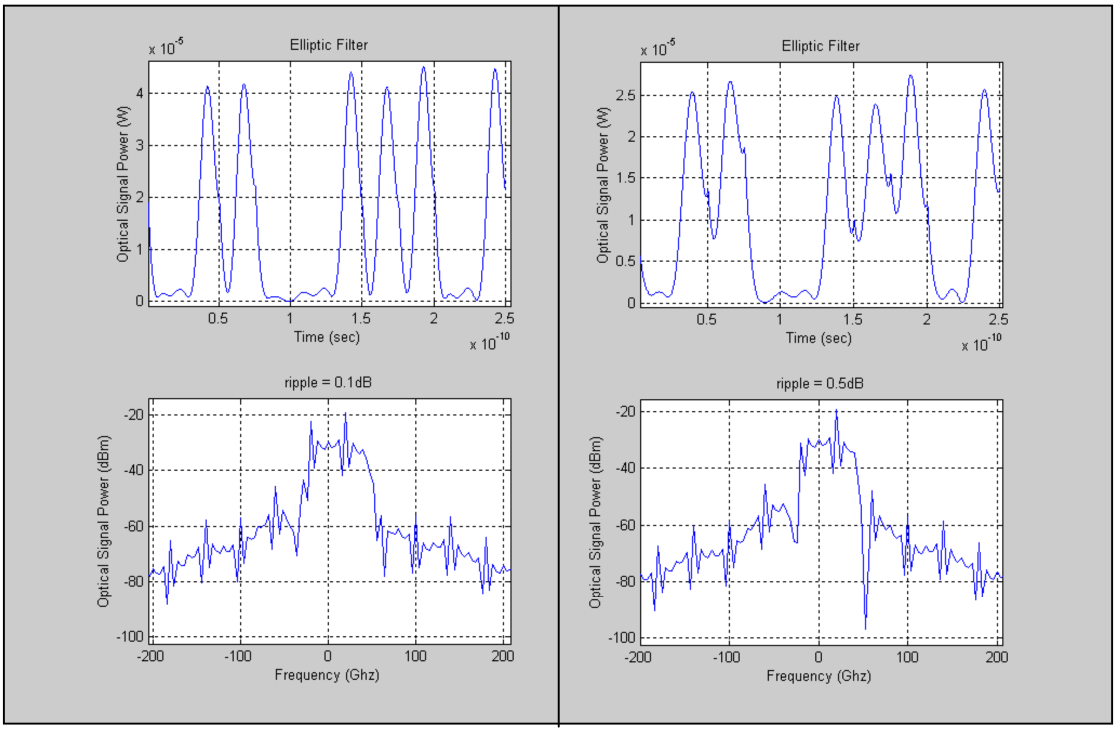

Figure 25 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from elliptic filter with the passband ripple of (a) 0.1dB and (b) 0.5dB

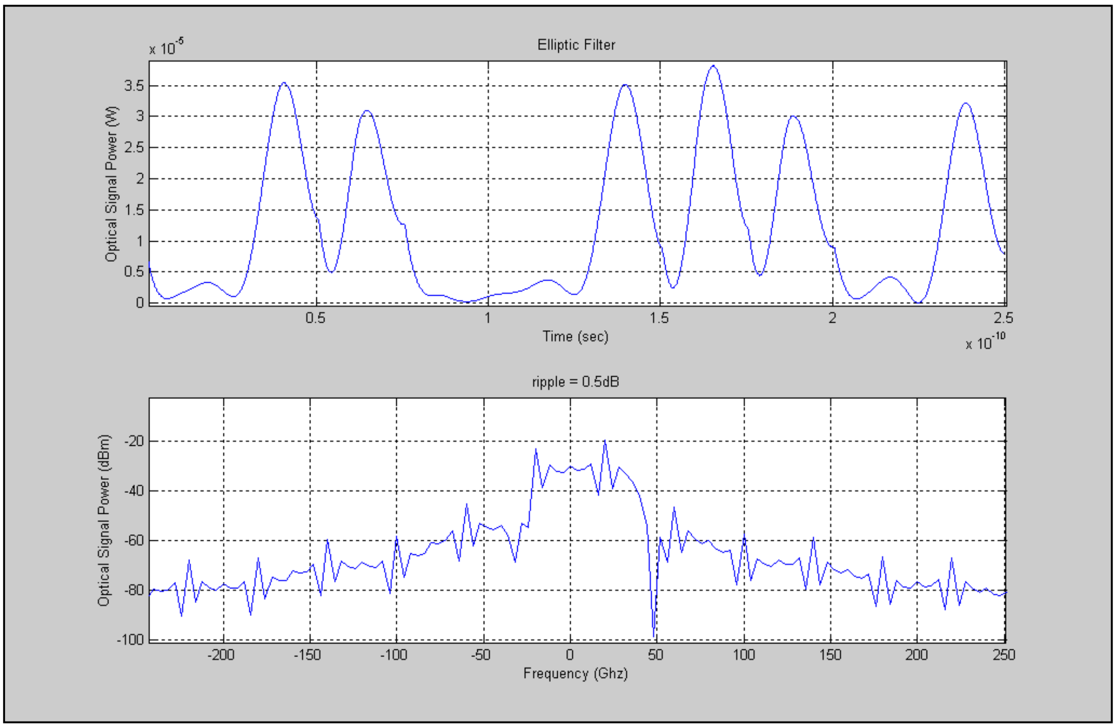

Figure 26 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from elliptic filter with the passband ripple of 0.5dB

However, the passband ripple will cause a distortion on the output signal spectrum, which may cause some noise and fluctuation at the pulses and reduce the signal power. Therefore, filter response with small ripple is still the preferable choice although it is not as sharp as others. These simulations are performed by using the characteristic of the elliptic filter.

9.2 Effects of Stop-band Roll-off

The stop-band Attenuation is the factor that determines the amplitude of fall-off of the filtered components. The design or choosing of stop-band attenuation will also affects the steepness of the roll-off region by increasing the number of pole, and filter order.

Figure 24 shows the Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from filtering of DSB CS-RZ by elliptic filter with the same centre frequency, same passband bandwidth of 50GHz, same passband ripples of 20dB and different stopband attenuation of 20dB and 40dB respectively. the VSB CS-RZ obtained from the elliptic filter with 40dB passband ripples clearly have a narrower $BW_{30dB\text{-}down}$, hence more lower sideband spectral has been filtered out. Again, this leads to an increasing of ‘0’ bit noise level.

Again, this problem can be solved by shifting the centre frequency of the filter in order to not to obtain a maximum of 3dB down at either lower or upper sideband, so that the pulse signals wont significantly affected by the noise level and able to be recovered after filtering. As shown in Figure 27, the signal pulses obtained are almost the same as the 20dB attenuated. However, the more attenuate on the undesirable components means that the average signal input power is reduced, and this may also results in less inter-symbol interference between adjacent symbols and improves system performance. These simulations are implemented by using the sharp roll off characteristic of elliptic filter.

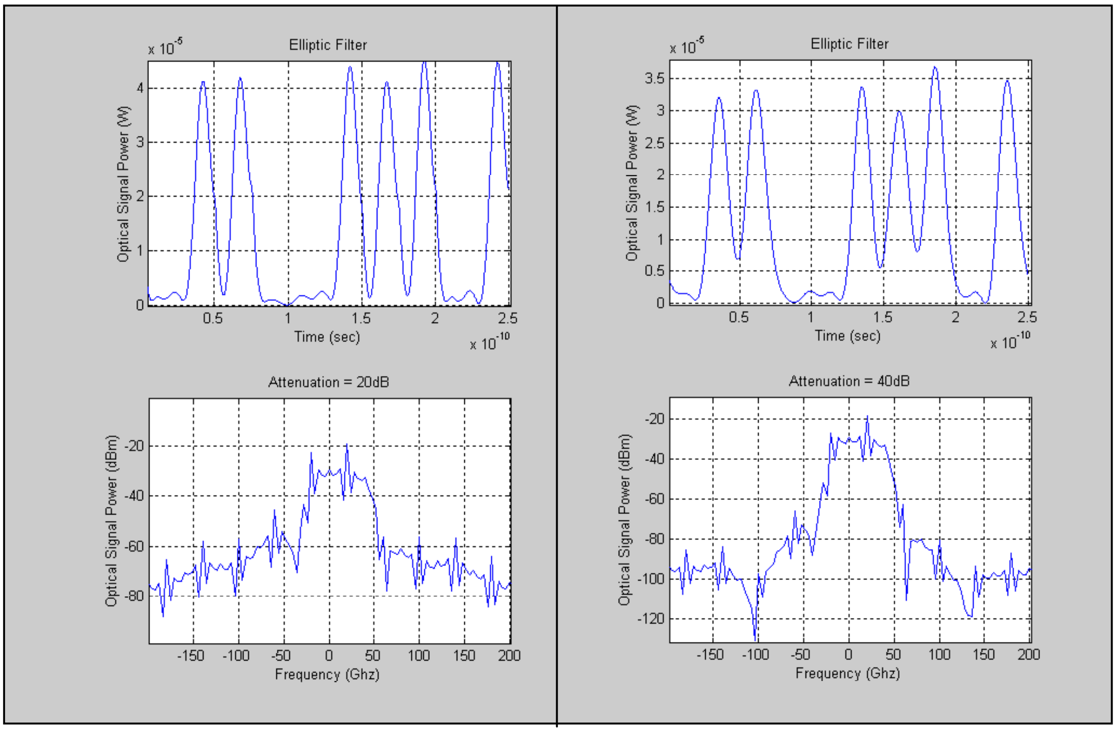

Figure 27 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from elliptic filter with the stopband attenuation of (a) 20dB and (b) 40dB

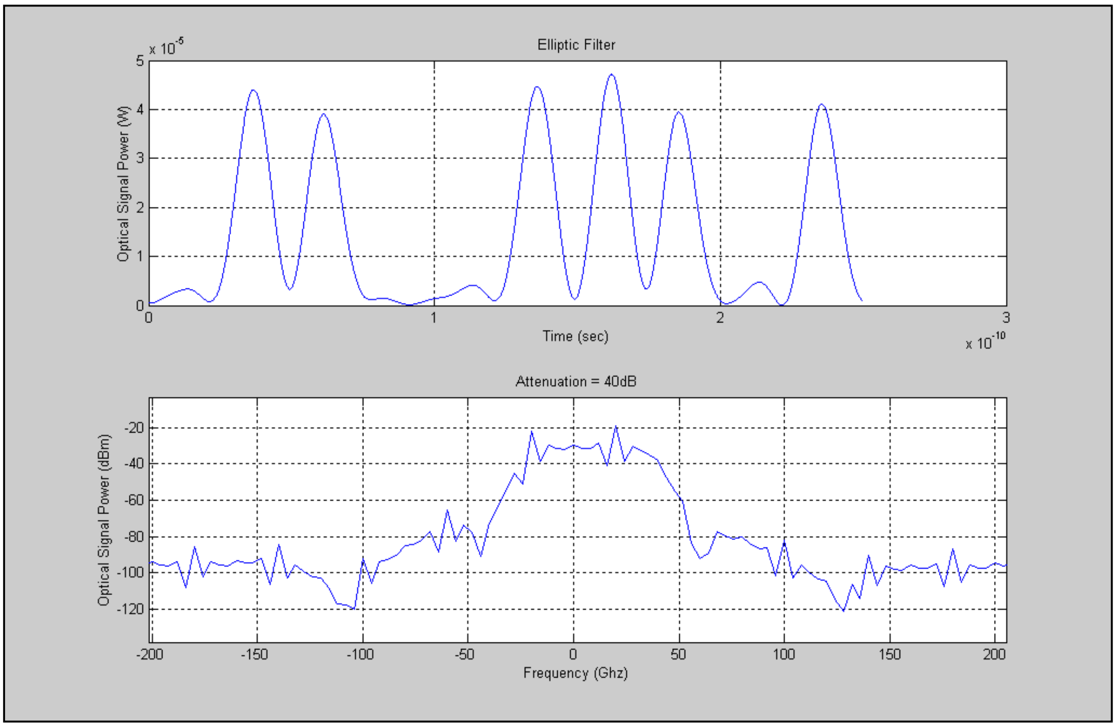

Figure 28 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from elliptic filter with the stopband attenuation of 40dB

9.3 Effect of Variable Roll-off Band

In this section, some simulation is implemented to investigate the effects on the filtered signal due to variable the roll-off steepness by varying the stopband bandwidth. This involves changing the filter order and the number of poles of the filter in the z-plane ie. The number of filter multi-layers, while the stopband bandwidth is being changed. However, the effect due to changing of stopband bandwidth is not significant unless the passband bandwidth is varied until the filtered signal seems almost the same before filtered as shown in Figure 29. The purpose of employing the VSB CS-RZ is to obtain better spectral efficiency; therefore, adding an optical filter would be redundant and does not produce any improvement in performance. Therefore, the sharper roll-off is preferable to optimum the function of *VSB*.

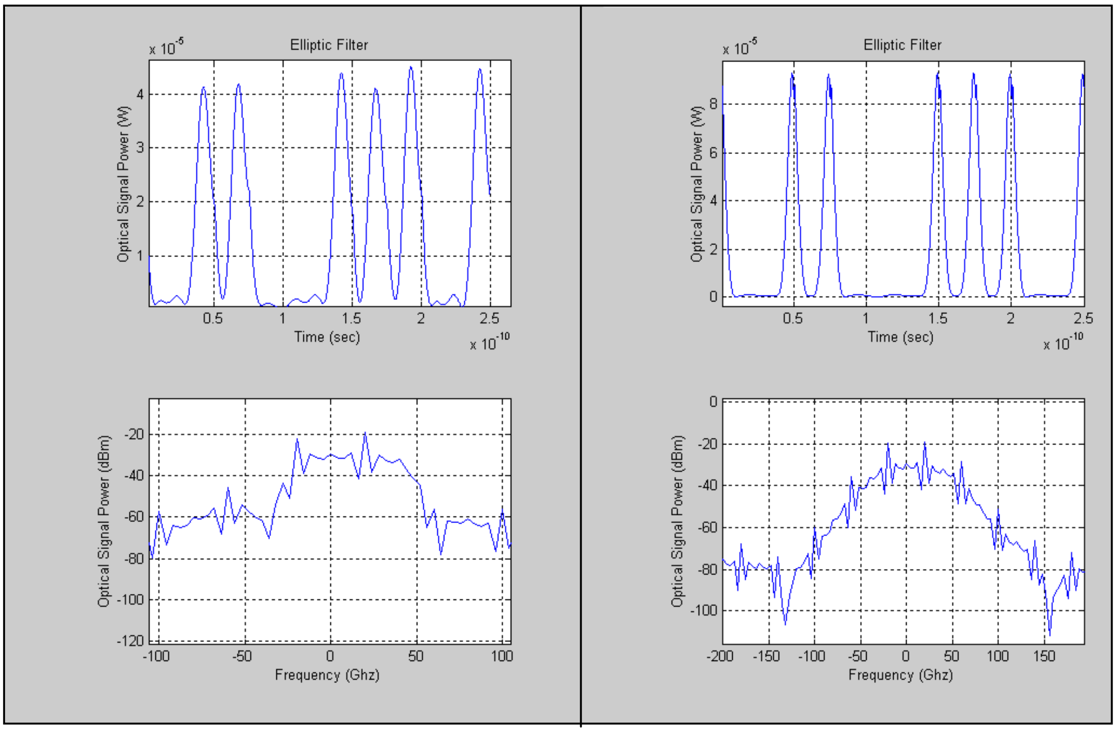

Figure 29 Optical power spectral density and corresponding signal pulse train of 40Gps VSB CS-RZ formatted signals at the out put of an elliptic filter.

9.4 Comparison of the Performance of Elliptic, Chebyshev and Butterworth over the VSB CS-RZ format

Three Infinite Impulse Response (IIR) filters, the elliptic, Chebyshev and Butterworth filters have been proposed for the generation of VSB format signals. Comparisons are made between them as an VSB filter for optical transmission system. From the previous part of this section, 40dB stop-band attenuation for the magnitude responses of the filter is superior to minimise inter-symbol interference and cross-talk. Therefore, the simulations and comparisons are conducted using the criteria of 40dB stop-band attenuation, 50 GHz pass-band bandwidth, and 0.1dB stop-band ripples.

9.4.1 Butterworth Filter and VSB format

The Butterworth Filter, with the magnitude response that is maximally flat in the pass-band and stop band which shows no ripple in either the pass band or stop band. The ripple less property of Butterworth filter has an advantage of prevent distortion at the signal inside the passband region, hence no power loss at the desired sideband; however the ripple less property has significantly reduced the steepness of the transition band.

The filtering effects from Butterworth filter are not significant since the roll-off region is too wide which including too much of unnecessary sideband components. As a result, it doesn't provide expected advantages of VSB over DSB. $BW_{30dB\text{-}down}$ of the VSB CS-RZ signal obtained is approximately 110GHz.

Note that, the stop-band bandwidth selected in the simulation is the minimum value (steepest roll-off) before the filter response become unstable, where the configuration of the filters are same as those stated in previous section..

Figure 3-6 shows the Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from Butterworth filter with 40dB stop-band attenuation, 50GHz pass-band bandwidth, and 0.1dB stop-band ripples, where the steepness of transition band also been optimise.

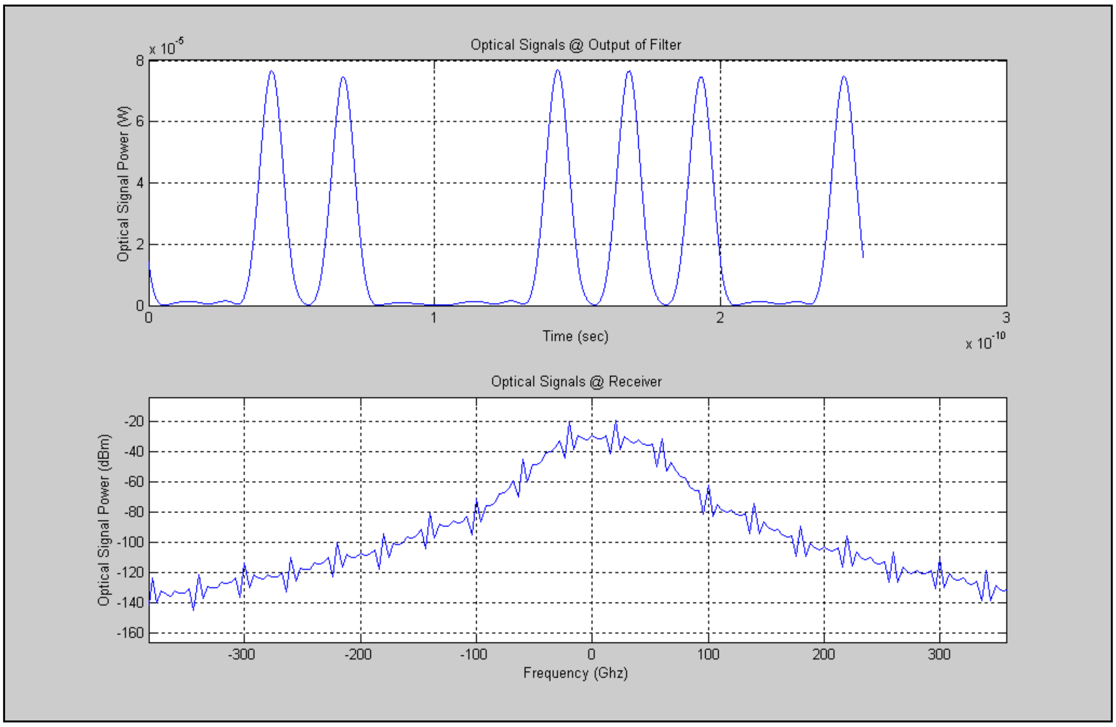

Figure 30 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from Butterworth filter with 40dB attenuation

9.4.2 Chebyshev Filter

The Chebyshev approximation which has ripples in either pass-band has a much more rectangular frequency response in the region near cut-off than the Butterworth family of filters. The effect of adding the ripple is steep roll off, which implies smaller roll off bandwidth. The larger the allowed ripple; the steeper will be the transition from the passband to the stopband. However, the ripples will cause some distortion at the filtred signal; therefore a smaller ripple is preferable. $BW_{30dB\text{-}down}$ of the VSB CS-RZ signal obtained is approximately 80GHz as shown in Figure 31.

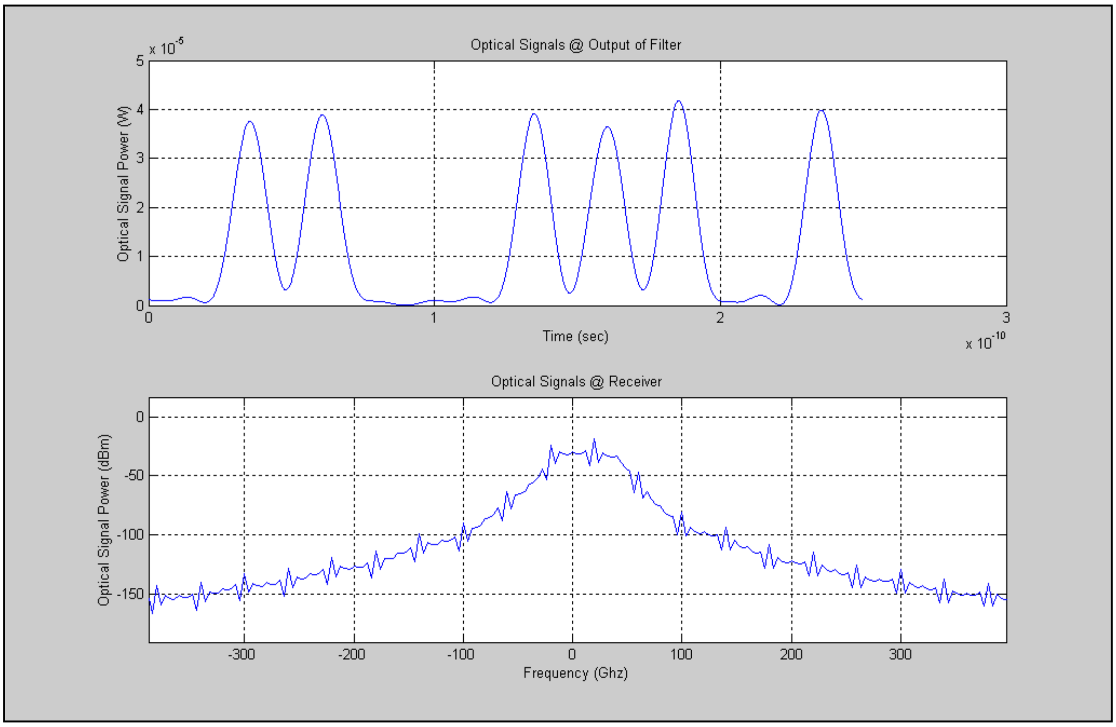

Figure 31 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from Chebyshev filter with 40dB attenuation

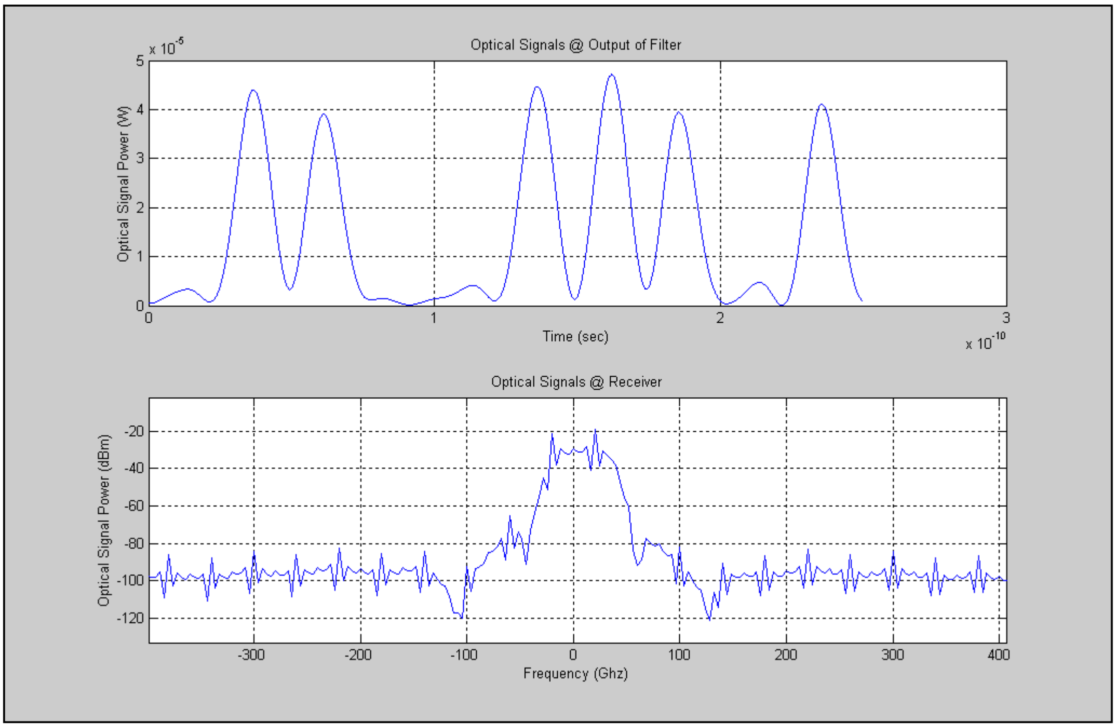

Figure 32 Optical power spectral density and corresponding signal pulse of 40Gps VSB CS-RZ format obtained from Elliptic filter with 40dB attenuation

9.4.3 Elliptic Filter

Elliptic filter which has equi-ripple response in both its pass band and its stop band even has a steeper roll-off. These are similar to finite-impulse-response (FIR) equi-ripple filters.

From Figure 32, $BW_{30dB\text{-}down}$ of the VSB CS-RZ signal obtained is approximately 80GHz as shown. Although the $BW_{30dB\text{-}down}$ is just narrower than the Chebychev approximation; but the VSB CS-RZ obtained is clearly sharper and 'cleaner' than the previous 2 signal spectrums shown, since most of the unwanted components have been filtered 40dB down. Therefore, it may conclude that elliptic filter is the most suitable choice for implemented for the VSB modulation module.

9.5 Comparison of SSB CS-RZ and VSB CS-RZ

Single Sideband Carrier-Suppressed Return-to-Zero (SSB CS-RZ) modulation format can be obtained from the filtering technique by excluding all the unwanted sideband components as shown in Figure 33. SSB CS-RZ though offers better $BW_{30dB\text{-}down}$; however this lead to the problem in recovering the signal. The filtered sideband needs to be re-inserted in order to recover the original bit stream. This shows the advantages of VSB CS-RZ over SSB CS-RZ.

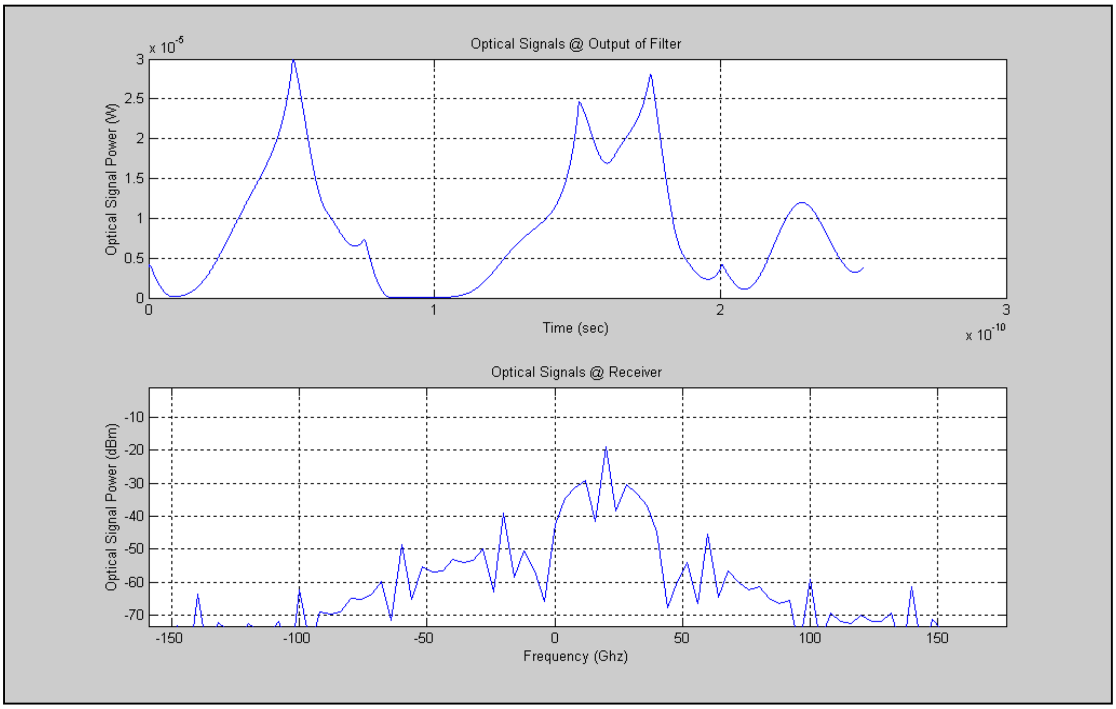

Figure 33 Optical power spectral density (lower trace) and the corresponding signal pulse of 40Gps SSB CS-RZ format (upper trace) at the output of an elliptic filter

The SSB-RZ format obtained from filtering on conventional RZ signal .

9.6 Concluding remarks

In summary, the effects on VSB CS-RZ modulation format due to filtering process have been discussed. It shows the criteria that should be followed in order to optimise the VSB CS-RZ modulation. From the comparison of performance of Elliptic, Chebyshev, and Butterworth filters on generation has shown that Elliptic has been superior. However, the simulation is only done for the 50GHz passband bandwidth, and the ripple of 0.1dB. Further works would be conducted to optimise the system. OtherFIR filters such as Remez and Kaisar approximation could be used and implemented. The advantage of FIR filter is its stability of the filter responses, however it computing intensive and large computing resources are needed for simulation of such filters in Tera-Hz systems.

9.7 Comparison of the Performance of VSB CS-RZ, DSB CS-RZ and Conventional RZ formats

In this section we compare the performance of VSB CS-RZ, DSB CS-RZ and conventional RZ modulation formats in long-haul 40Gbps systems using a number of typical system performance parameter. Several factors are taken into account in investigation of the performance, such as dispersion, non-linear effect, noise, and spectral efficiency. The simulation is implemented by propagating the signal through the fibre over a certain distance, and measure the system performance using the eye diagram.

10 Pulse Propagation of Optical Signals in the Fibre

As outlined in previous sections the dispersion and nonlinear tolerance can be estimated by numerical simulations, where the propagation of the pulses is modelled by the nonlinear Schrödinger equation and is solved by the Split-Step Fourier method. However, some of the non-linear effects such as Stimulated Brillouin (SBS), Stimulated Raman Scattering (SRS), and Four Wave Mixing (FWM) are excluded from the model, since these effects can be minimised by the use of dispersion management,. XPM and SPM are included in the nonlinear Schrodinger equation used to model the propagation of optical field inside fibre.

11 Performance Comparisons between CS_RZ DSB and CS_RZ VSB modulation formats

The performances of VSB CS-RZ format, DSB CS-RZ format, and conventional RZ format are investigated by observing the signal before and after transmitted over the same distance.

As seen from Figure 34, VSB CS-RZ modulation has shown superior in transmission compared to DSB CS-RZ and conventional RZ format, since the Gaussian pulses would not suffer any distortion and are immune to the non-linear effects from the fibre after the transmission.

11.1 BER Measurement

In optical communication systems, the eye diagram is used to visualize how the waveforms used to send multiple bits of data can potentially lead to errors in the interpretation of those bits. This is the so-called problem of inter-symbol interference. The BER of the systems are calculated with the δ factor obtained from the eye diagram. The Q factor measured for the VSB CS-RZ is 8, that is a BER of approximately 10^{-12}.

11.2 Comparisons of Spectral Efficiency

High spectral efficiency is the key consideration for the DWDM optical communication systems, since it determines the total number of channel and the channel spacing which can be multiplexed in the systems.

11.3 Conclusion

VSB-CS-RZ format has shown the better performance in spectral efficiency and robustness in BER compared to DSB CS-RZ and conventional RZ format. Therefore, VSB CS-RZ modulation format has a promising performance and future in the Multi era bps DWDM optical communication system.

Figure 37 shows the simulation done on the filtering of DSB CS-RZ modulated at the carrier (suppressed) of 1550nm with an elliptic filter at the centre frequency of 193.412 THz and a passband of 50GHz. As shown, the upper sideband is included in the passband region, while the lower sideband is placed in the roll-off region of the filter response where most of the sideband will be filtered off but not all of it.

Figure 38 shows the power spectral of VSB CS-RZ signal at the output of the filter, where the lower sideband is 3dB down compare to the upper sideband. Although the spectral width between the upper and lower sideband remains 40GHz after filtering, but most of the spectrum at the lower sideband clearly has been filtered off. This resulting a Gaussian-like bit stream in RZ format, while the filtering process causes some noise at the ‘0’ level and fluctuation at the power level for ‘1’. The performance of the VSB CS-RZ will be stated in the last section.

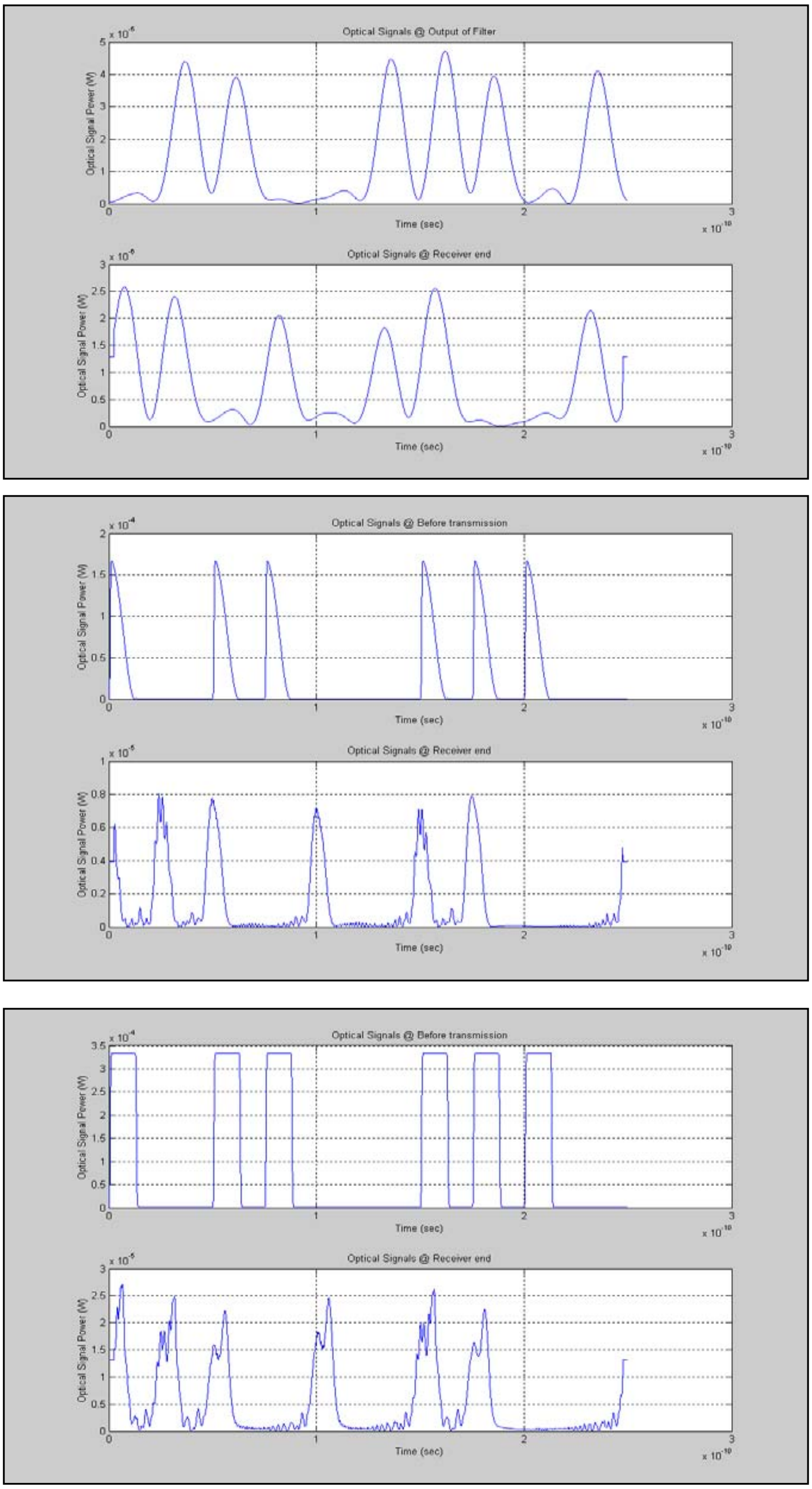

Figure 34 Signal Comparison before and after transmission (a) VSB CS-RZ (b) DSB CS-RZ and (c) Conventional RZ format

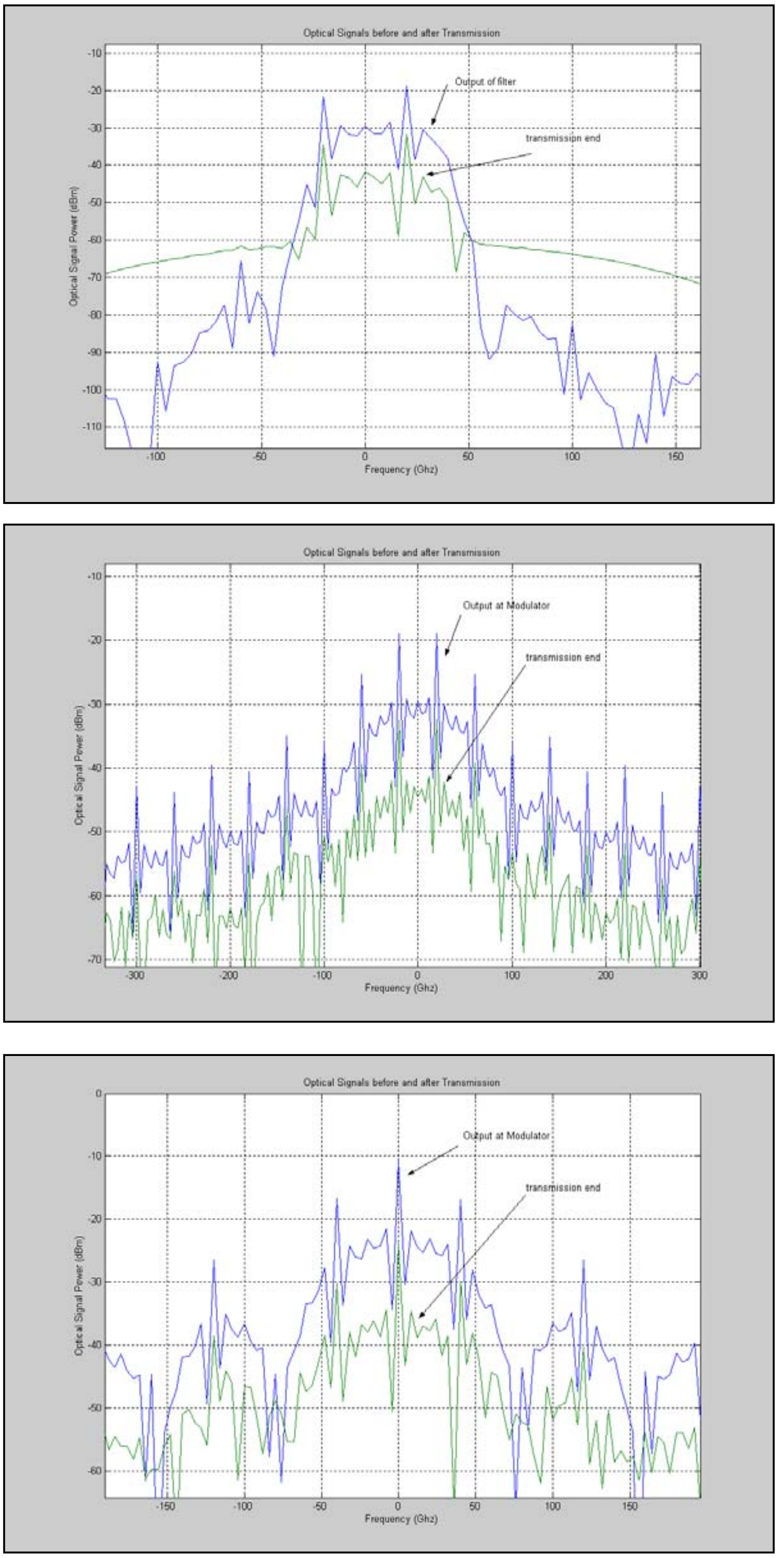

Figure 35 Signal Power Spectrum before and after transmission (a) top trace VSB CS-RZ (b)middle trace DSB CS-RZ and (c)bottom trace Conventional RZ format

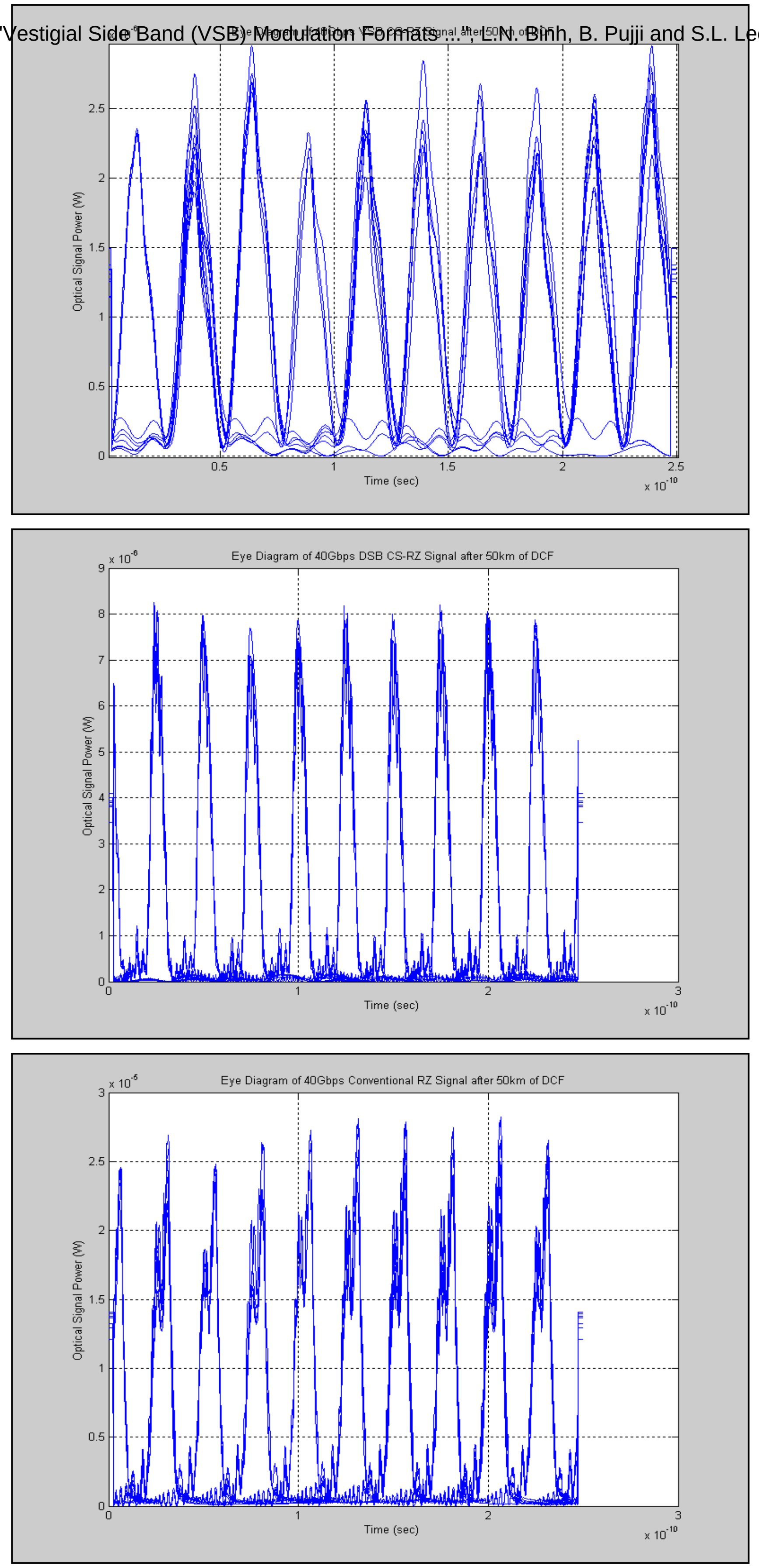

Figure 36 Eye Diagram after transmission for (a)top trace VSB CS-RZ (b) Middle traceDSB CS-RZ and (c)bottom trace Conventional RZ format

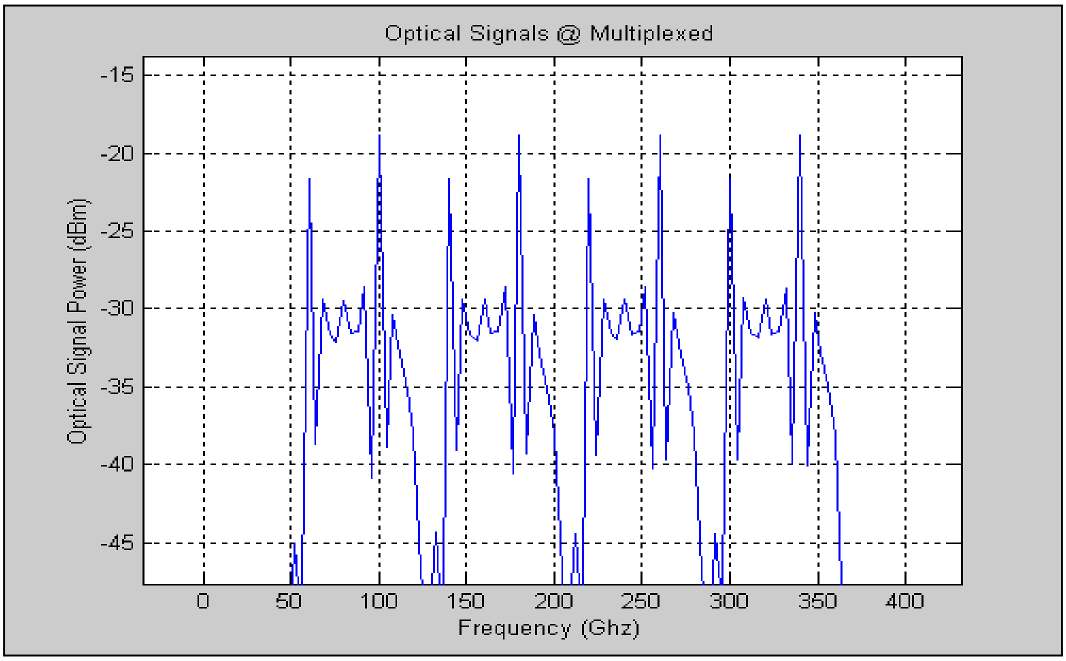

Figure36 Spectral distribution of 4 multiplexed channels of 40Gbps signal/channel with the channel spacing of 80Ghzconsidered to be sufficient for 40GHz VSB CS-RZ signal but not for the DSB CS-RZ where the spectral cross-talk appeared between the adjacent channels.

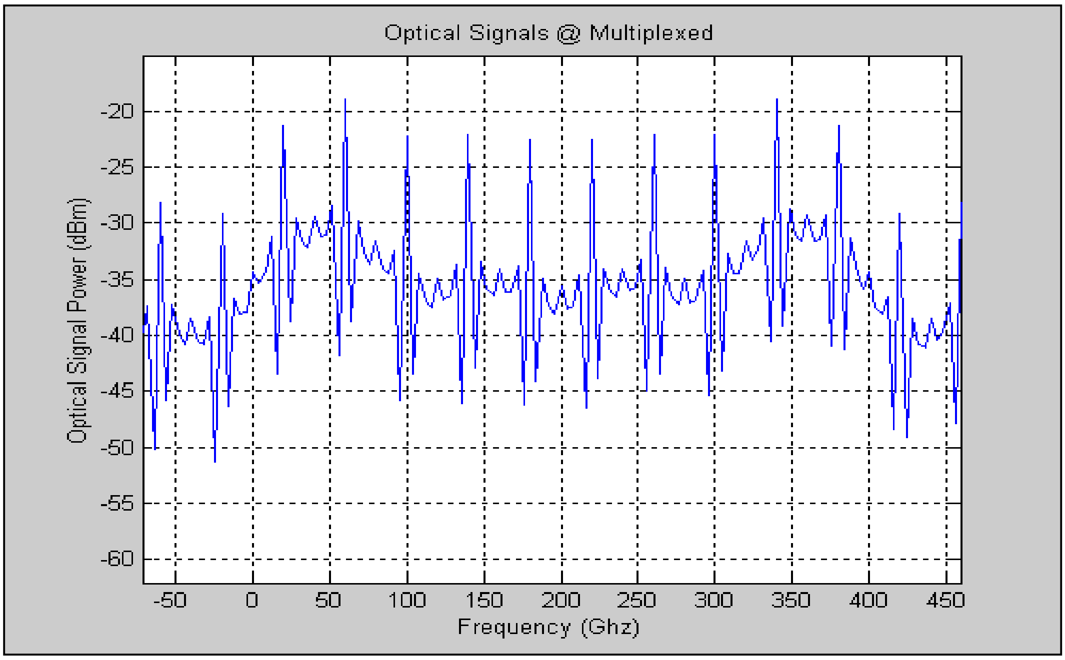

Figure37 Signal Power Spectrum multiplexed with 80GHz Channel Spacing (a) VSB CS-RZ (b) DSB CS-RZ

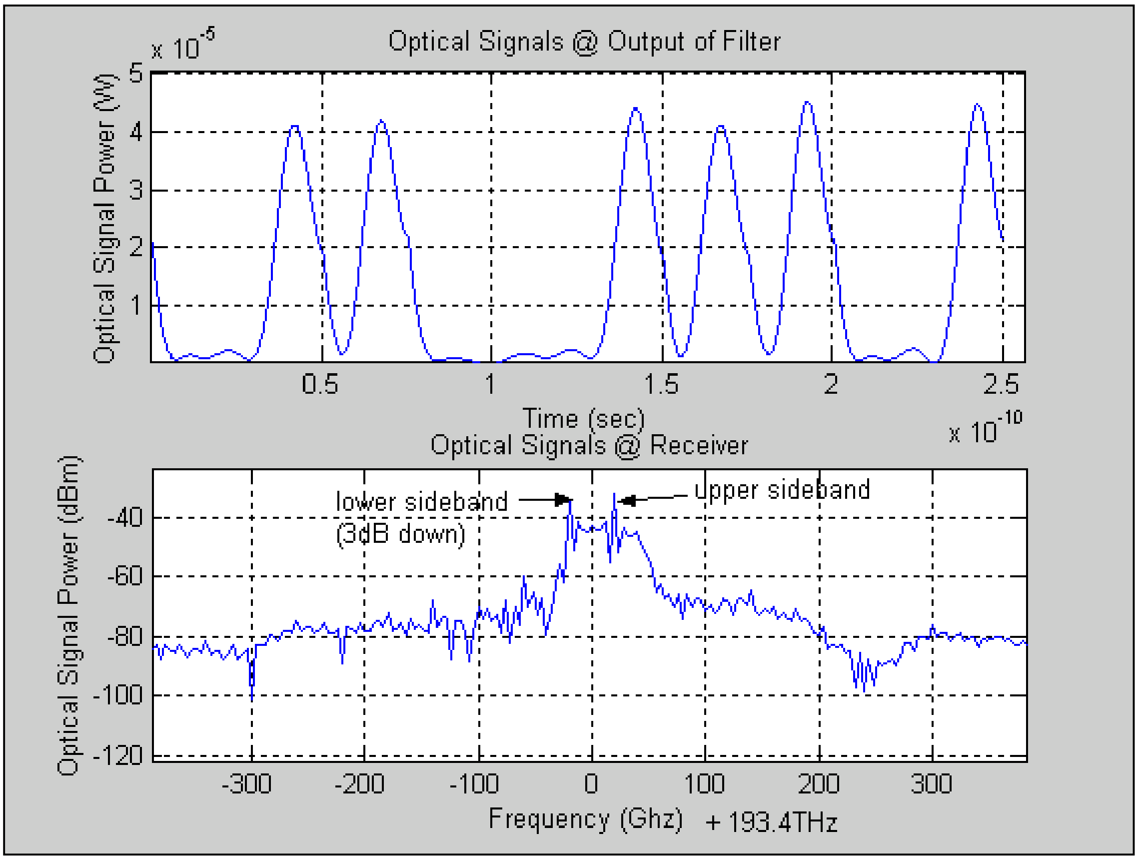

Figure 38 Optical signal power and corresponding power spectral density of 40Gps VSB CS-RZ format with a bandwidth of 40 GHz between 2 sidebands

11.4 Signal Characteristics of VSB CS-RZ Compared to DSB CS-RZ Modulated at 40Gbps

Spectral bandwidth of the signal is the prominent issue for WDM and DWDM systems since it is decisive for the channel spacing, where the ITU standard is 100 GHz and 50 GHz respectively. Figure 1-6 shows the optical signal spectrum of the DSB CS-RZ and VSB CS-RZ modulated lightwaves. One way to determine the signal bandwidth is to measure at the 30dB-down from the peak power amplitude. For DSB CS-RZ, the $BW_{30dB\text{-}down}$ is approximately 200GHz while it is only 78GHz for VSB CS-RZ. The unwanted frequency components are filtered 20dB down in the VSB CS-RZ which reduce the signal bandwidth; and hence prevent the spectral crosstalk between the adjacent WDM or DWDM channels, or else the channel spacing can be reduced.

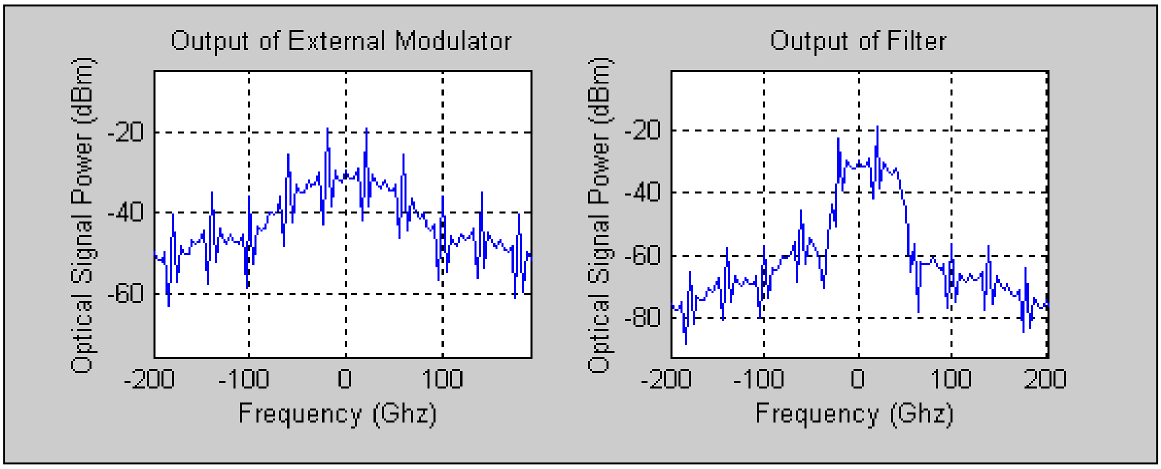

Figure 39 Optical Signal Spectrum of (a) DSB CS-RZ (b) VSB CS-RZ signal modulated at 40Gbps

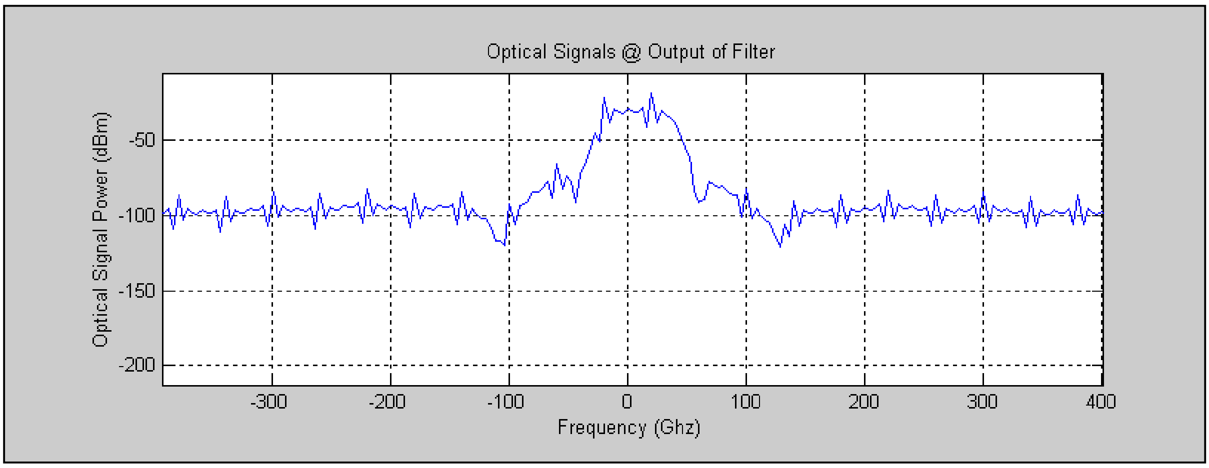

Figure 40 Optical Signal Spectrum of VSB CS-RZ signal modulated at 40 Gbps (unwanted components - 40dB down)

Figure 40 shows the VSB CS-RZ signal spectrum which involving attenuation of 40dB on the unwanted components; hence obtain the $BW_{30dB\text{-}down}$ of approximately 60 GHz.

11.5 Concluding remarks

In summary, the VSB CS-RZ modulation format has been introduced by optical filtering the output of DSB CS-RZ modulator and propagating through the guided wvae medium. The simulation has taken into account practical limitations of the modulation formats in practical system. The $BW_{30dB\text{-}down}$ of the signal has been reduced from 200GHz in DSB CS-RZ to 78GHz or even lower in VSB CS-RZ, thus significantly narrow the channel spacing and eliminate the spectral crosstalk. The spectral efficiency of the VSB CS-RZ needs to be optimised by tuning the filter pass and roll off bands as well as the band ripple. The issues of the deign of optical filters have been described and impacts of the filter pass and cut off bands on the signal distortion have been studied. It is very critical that the manufacturing of the filters must be precise, multiplayer thin-film structures would offer the best filters for VSB format generation.

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13 APPENDIX A: Optical Filters Analysis and Design

This appendix develops a model for a VSB bandpass filter that provides VSB CS-RZ modulation format. This involves filtering out most, but not all of the unwanted sideband from the DSB CS-RZ signal. Various digital filter designs such as Butterworth, Chebyshev and Elliptic filter designs are described and discussed in this section. Analyses of the Infinite Impulse Response Filters, Butterworth, Chebyshev and Elliptic filters are given to determine their passband characteristics, and their suitability in system transmission will be examined. The design of the filters is to meet specific criteria as set out in previous sections. The digital filter design initiates from an analog filter, and then converting it into a digital filter for implementation.

13.1 Analog Filter Design

There are several methods commonly used in designing a filter, such as Butterworth, Chebyshev and Elliptic filter designs. However, these basic techniques are only available for lowpass filters. Therefore, frequency transformation is needed in order to convert a lowpass filter into a bandpass or a band-reject filter.

13.2 Butterworth Lowpass Prototype Design

Butterworth response is normally called the "maximally flat" response with minimum ripple in the passband and stopband region. Its magnitude-squared function is defined by

$$\left|H_{LP}(j\omega)\right|^2 = \frac{1}{1+(\omega/\omega_c)^{2N}} \quad \text{or} \quad \left|H_{LP_P}(j\omega)\right|^2 = \frac{1}{1+(\omega)^{2N}} \qquad (A1)$$

where N is the order of the filter and ωc is defined as the cutoff frequency where the filter magnitude is $1/\sqrt{2}$ times the dc gain at ω = 0, which is also the 3-dB cutoff. For a cutoff, or critical frequency of 1, the result is called a (normalized) prototype lowpass filter.

For a Butterworth filter response, the poles of $H_{LP_P}(s)H_{LP_P}(-s)$ are the roots of

$$(-1)^N s^{2N} = -1 = e^{j(2k-1)\pi} \qquad k = 0, 1, 2, \ldots, 2N-1$$

Therefore, the poles S_k are then given by

$$s_k = 1e^{jk\pi/N} \qquad \text{N is odd} \qquad (A2)$$

$$s_k = 1e^{j(\pi+k2\pi)/2N} \qquad \text{N is even} \qquad (A3)$$

or simply by

$$s_k = e^{j[(2k+N-1)/2N]\pi} \qquad k = 0,1,2, \ldots, 2N \qquad (A4)$$

sk could then be expressed as $s_k = \sigma_k + j\omega_k$, where the real and imaginary parts are given by

$$\sigma_k = \sin\left(\frac{2k-1}{N}\right)\frac{\pi}{2} \qquad \omega_k = \cos\left(\frac{2k-1}{N}\right)\frac{\pi}{2} \tag{A5}$$

With equation (A1.4) and (A1.5), the transfer function of the Butterworth lowpass prototype response for specific order of filter could easily be obtained.

$$N = \frac{\log_{10}\left(10^{-(M_{dB}/10)} - 1\right)}{2\log_{10}\omega_a} \tag{A6}$$

Equation (A.6) is used to detrmine the filter order needed due to the gain (M) specification at $\omega = \omega_a$.

13.3 Chebyshev Lowpass Prototype Design

Unlike the maximally flat approximation made in previous section, the Chebychev filter is known as equal-ripple filter with equal-ripple in the passband; and for an inverse-Chebychev filter, there is equil-ripple at the stopband. However, only Chebychev filter with equal-ripple in the passband is being considered in our works. The equal-ripple in the passband allows the amplitude response to have a steeper rolloff outside the passband for a fixed filter order.

The magnitude-squared characteristic of a lowpass prototype Chebyshev filter is given by

$$\left|H_{LP_P}(j\omega)\right|^2 = \frac{1}{1+\varepsilon^2 C_N{}^2(\omega)} \tag{A7}$$

where N is again the order of the filter, and ε is the parameter to set the ripple amplitude in the passband as shown in (A8).

$$r_{dB} = 10\log_{10}\left(1+\varepsilon^2\right) \tag{A8}$$

The equal-ripple property is brought about by the use of Chebyshev cosine polynomials defined as

$$C_N(\omega) = \cos\left(N\cos^{-1}\omega\right) \qquad 0 \le \omega \le 0 \tag{A9}$$

$$C_N(\omega) = \cos\left(N\cos^{-1}\omega\right) \qquad \omega > 1 \tag{A10}$$

With the initial conditions of $C_0 = 1$ and $C_1 = \omega$, the Nth-order Chebychev polynomials can obtained by applying equation (A5) which is derived from (A9) and (A10).

$$C_{N+1}(\omega) = 2\omega C_N(\omega) - C_{N-1}(\omega) \qquad (A11)$$

The Chebyshev polynomials is used to determine the filter order by substitute the CN(ω) back into (A2.1), to obtain the gain (M) specification, where $\left|H_{LP_P}(j\omega)\right| = M$.

$$\beta_k = \frac{1}{n}\sinh^{-1}\frac{1}{\varepsilon} \qquad (A12)$$

βk is introduced to work out all the location of the poles, in order to find out the transfer function of the Chebychev lowpass prototype response for the specific filter order.

The poles, $s_k = \sigma_k + j\omega_k$ of the equal-ripple approximant are located on an ellipse in the s plane, given by

$$\frac{\sigma_k^{\;2}}{\sinh^2\beta_k} + \frac{\omega_k^{\;2}}{\cosh^2\beta_k} = 1 \qquad (A13)$$

The normalised pole locations, s'k with normalising factor of coshβk are expressed as

$s'_k \cong \sigma'_k + j\omega'_k$,

where $\sigma'_k = \tanh\beta_k \sin\left(\frac{2k-1}{n}\right)\frac{\pi}{2}$ $\qquad \omega'_k = \cos\left(\frac{2k-1}{n}\right)\frac{\pi}{2}$ (A14)

Therefore the re-normalised Chebychev filter poles, S_k can simply be obtained by multiply s'k by coshβk. As we can see in equations (A12-A14), the magnitude of the ripple in the passband region affects the transfer function of the Chebychev response.

13.4 Elliptic Lowpass Prototype Design

The Elliptic filter is a combination of the Chebychev and inverse-Chebychev filters in that the Elliptic filter has amplitude response ripples in both the passband and stopband. The advantage of the elliptic filter is that for a given allowable ripple in the passband and a minimum attenuation in the stopband, the width of the transition band is minimized.

The magnitude-squared response of the Elliptic lowpass prototype of order N is given by

$$\left|H_{LP_P}(j\omega)\right|^2 = \frac{1}{1+\varepsilon^2 E_N{}^2(\omega)} \qquad (A15)$$

where $E_N^2(\omega)$ is a Chebychev rational functionobtained from the specified ripple characteristics.

$$R = \omega_{2P} / \omega_{1p} \qquad (A16)$$

R in (2)is known as selectivity factor, which represents the sharpness of the transition region, where ω_{1P} is the passband ripple-edge frequency and ω_{2P} is the stopband ripple-edge frequency. In elliptic lowpass prototype, the geometric mean of ω_{1P} and ω2P is at ω = 1, where it is also the passband ripple-edge frequency in Chebychev lowpass prototype, and the cut-off frequency for Butterworth lowpass prototype.

The transfer function of the lowpass prototype elliptic filter of order N is given by

$$H_{LP_P}(s) = \frac{H_o}{D(s)} \prod_{i=1}^{r} \frac{s^2 + A_{0i}}{s^2 + B_{1i}s + B_{0i}} \qquad (A17)$$

where $r = \frac{N-1}{2}$ when N is odd and

$= \frac{N}{2}$ when N is even (A18)

and $D(s) = s + s_0$ when N is odd and

$= 1$ when N is even (A19)

Given that D(s) is the single pole factor with a pole at $s = -s_0$ for N is odd, and D(s) = 1 for N is even. A_{0i} is the numerator coefficients that determine the zeros, while B_{0i}

and B_{1i} are the denominator coefficients that determine the pole positions in the s-plane. The transfer function of the elliptic lowpass response can be obtained by referring to Table 1.

13.4.1 Filter Transformations

In the previous sections emphasis has been placed on design procedures for the normalized filter prototypes that are low-pass filters having bandwidth of 1 rad /s. The design procedures can then be extended by converting the normalized filter to non-prototypes (un-normalized) bandpass and bandstop filters using the transformation Table 1. The transformation procedure is just simply by converting the frequencies, ω of the bandstop or bandpass filter to the normalized low pass prototype ω_{LP_P} to determine the transfer function $H_{LP_P}(s)$, and finally replace the Laplace variable s in the prototype with the s-transformation shown to obtain H(s).

Filter Type	ω-form to find ω_{LP_P}	s-form to find H(s) from $H_{LP_P}(s)$
Bandpass filter	$\omega_{LP_P} = \dfrac{\omega_{BP}^2 - \omega_o^2}{B\omega_{BP}}$	$\dfrac{s^2 + \omega_o^2}{Bs}$
Bandstop filter	$\omega_{LP_P} = \dfrac{B\omega_{BS}}{-\omega_{BS}^2 + \omega_o^2}$	$\dfrac{Bs}{s^2 + \omega_o^2}$

Table 1 Frequencies transformation to band-pass and band-stop filter

13.5 MATLAB Design of Butterworth Type Band pass filter

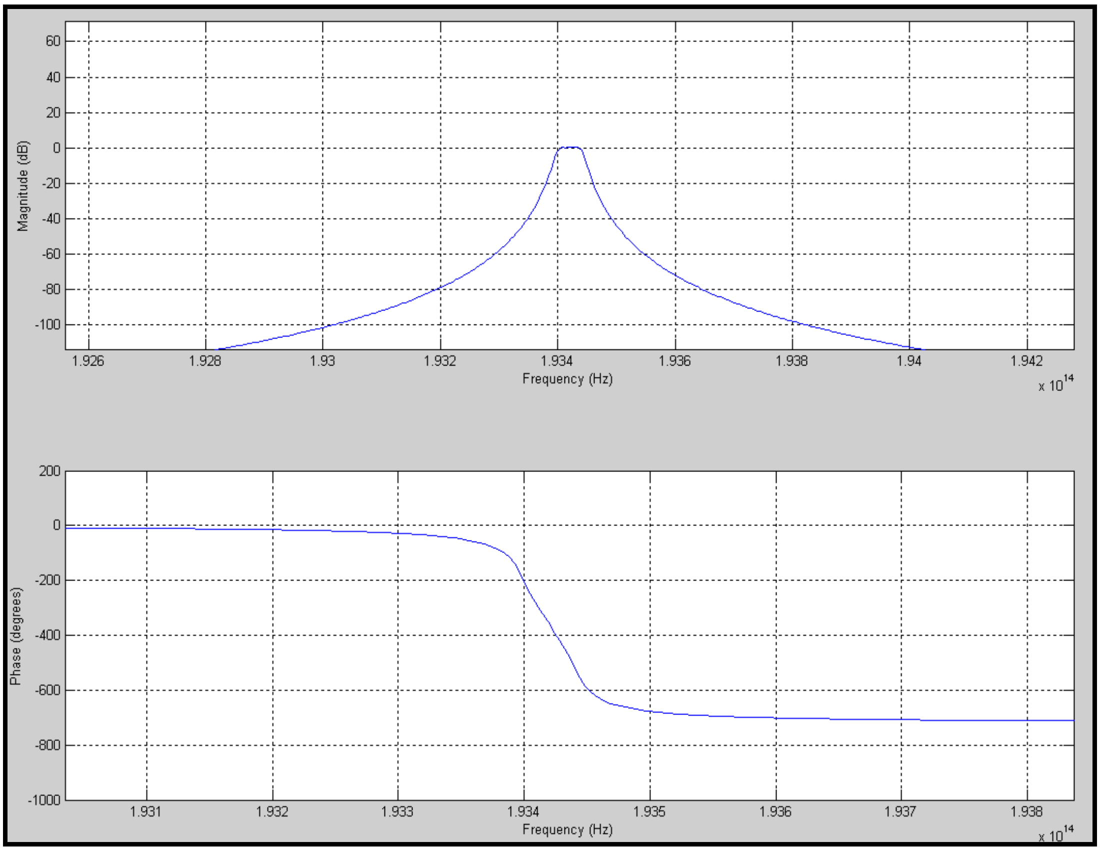


Fig A2.1: Frequency Response of Butterworth filter

Using Matlab© to simulate the Butterworth filter involves the following steps:

- It was first required to find the low pass analog prototype poles, zeros, and gain.
- This low pass filter was then transformed to the equivalent band pass with the desired cut-off frequencies.
- For digital filter design, bilinear transformation was used to convert the analog filter into a digital filter.
- The resultant is the required filter transfer function.

The results of this simulation with is shown below

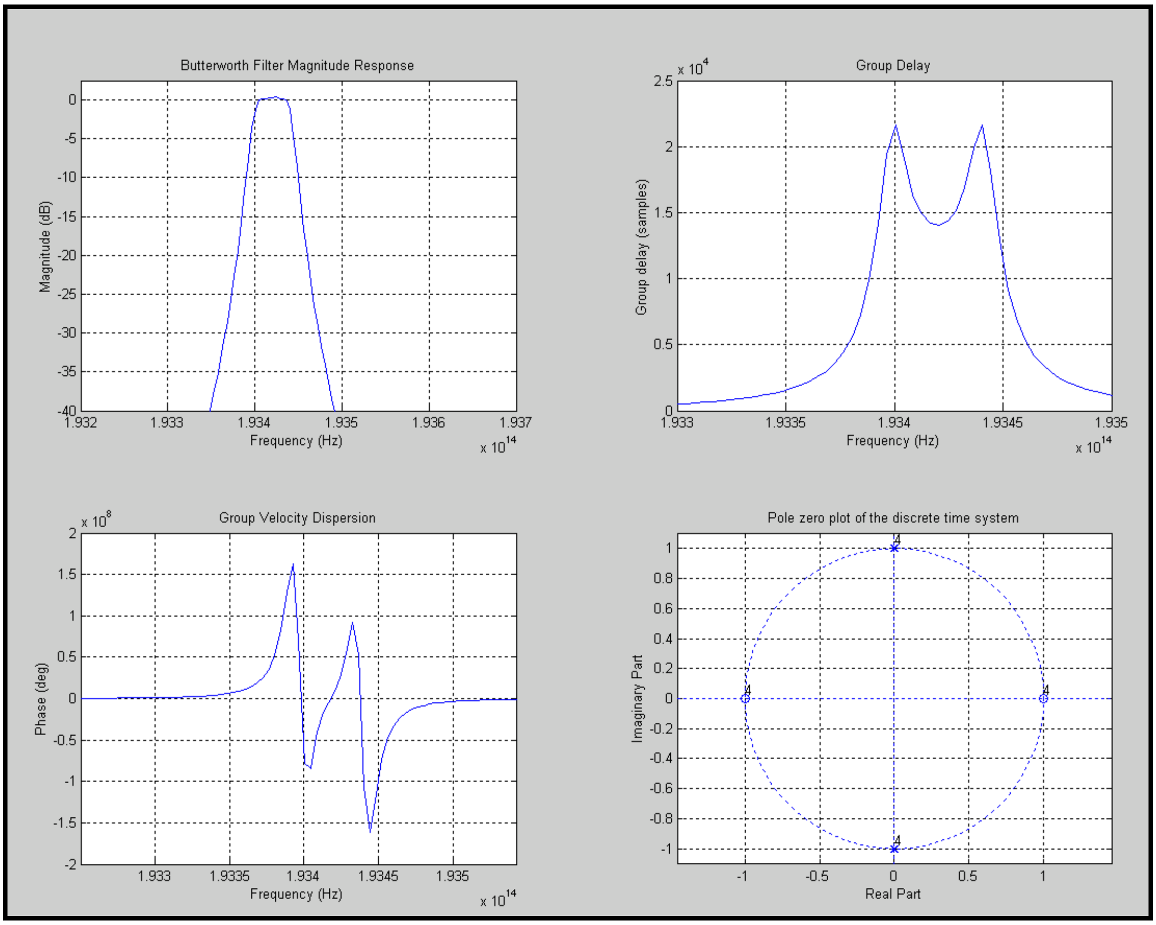


Fig A2.2: Butterworth type filter characteristics

The optical filter thus obtained was of order 4. Considering the frequency response of the Butterworth filter, shown in the top left quadrant in Figure A2.2, we observe that the 6 dB bandwidth of the filter was estimated to be 15GHz. The passband ripple was in accordance expectation at approximately 0.1%. This is a desired characteristic, as a flat pass band would lead to an equal increase in magnitude of frequencies within the pass band and thus less distortion. The magnitude to –40dB is at 60GHz and to –20dB at 30GHz.. This roll-off parameter is fairly crucial in order to suppress one of the side bands of the spectrum distribution of the RZ pulses in order to generate, RZ pulses with VSB modulation. It is interesting to note from the phase spectrum, shown in the lower half of Figure A2.1, that the phase response is fairly linear in passband region of the optical filter. The therefore implies a fairly constant group delay in the pass band, this is shown in the upper right quadrant. The corresponding group velocity dispersion is shown in the lower left quadrant of Figure A2.2. The pole zero plot, in the lower right quadrant shows all poles inside the unit circle and therefore implies a stable filter. The optical filter transfer function in the discrete domain is given by:

$$\frac{1.145\text{x}10^{-15} - 4.58\text{x}10^{-15} z^{-1} + 6.87\text{x}10^{-15} z^{-2} - 4.58\text{x}10^{-15} z^{-3} + 1.145\text{x}10^{-15} z^{-4}}{1 + 4.87x10^{-4} z^{-1} + 3.99z^{-2} + 1.46x10^{-3} z^{-3} + 5.997z^{-4} + 1.461x10^{-3} z^{-5} + 3.99z^{-6} + 4.87x10^{-4} z^{-7} + 0.999z^{-8}}$$

(*A21***)**

13.6 Chebychev Type Band pass filter

The Chebychev approximation to an ideal filter has a much more rectangular frequency response in the region near cut-off than the Butterworth family of filters. This is only possible with the addition of ripple in the either the pass band (Chebychev I: equiripple in pass band and monotonic in stop band) or in the stop band (Chebychev II: equiripple in stop band and monotonic in pass band: Figure A2.3), we will look at Chebychev I for this illustration. The effect of adding the ripple is steep roll off, which implies smaller roll off bandwidth. The larger the allowed ripple; the steeper will be the transition from the passband to the stop band. If no ripples are permitted, the Chebychev filter degenerates to a Butterworth filter. Its low pass equivalent magnitude squared function is:

$$|H_{LP}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 C^2{}_N(\omega)} \qquad (A22)$$

where the Nth order Chebychev polynomial is

$$C_N(\omega) = \cos\left(N\cos^{-1}\omega\right), \qquad \text{for } 0 \le \omega \le 1$$

and

$$C_N(\omega) = \cosh\left(N\cosh^{-1}\omega\right), \qquad \textbf{for}\, 1 > \omega$$

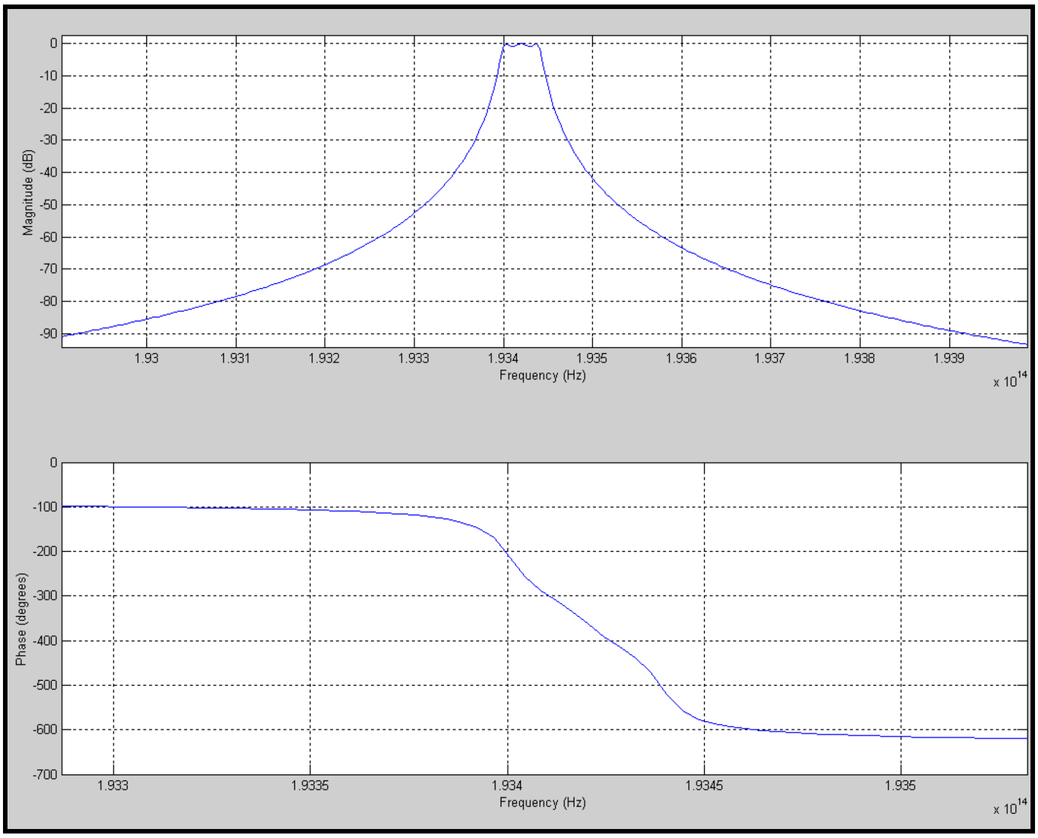
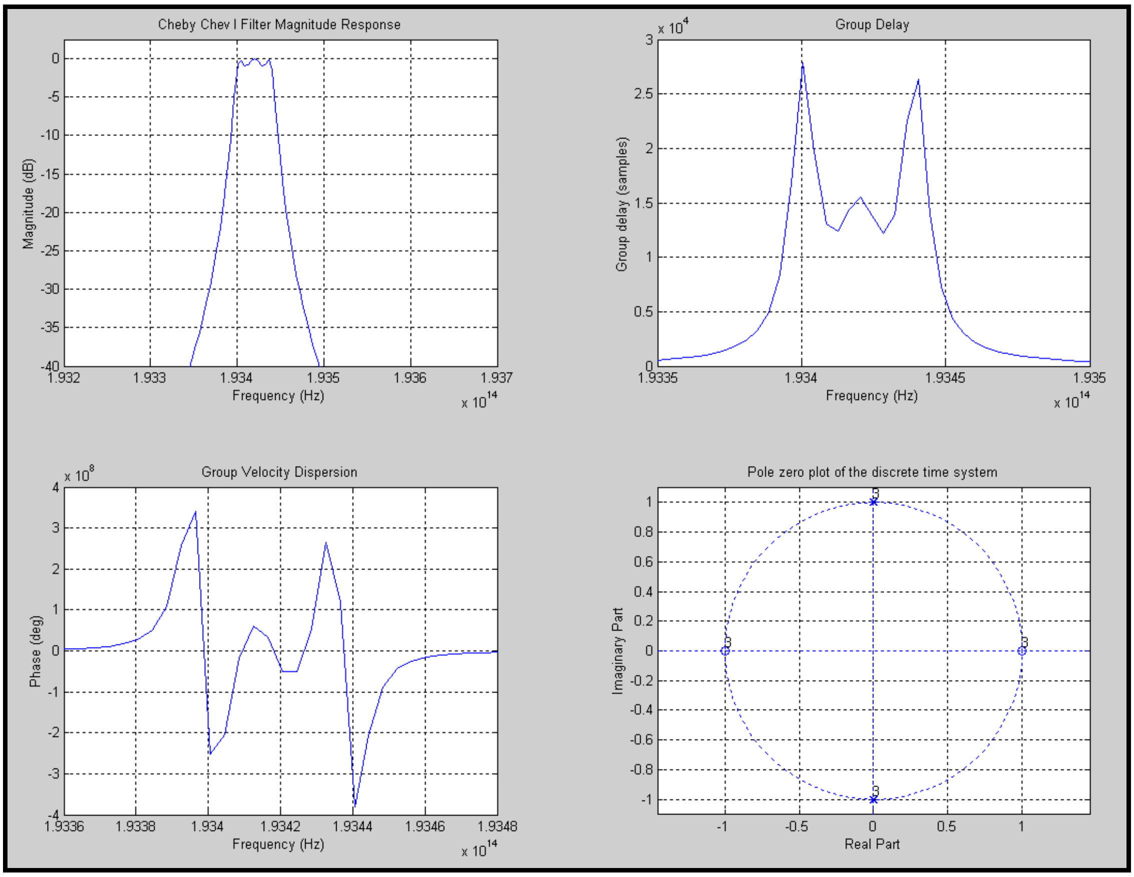


Fig A2.3: Frequency Response of ChebcChev I type Filter

The use of Matlab© for simulation purposes simplifies the use of Chebychev polynomial. Figure A2.3 shows the frequency response of the Chebychev I filter, it shows the ripple in the pass band and shows monotonic behaviour in the stop band.

- Using Matlab© to simulate the Chebychev filter involves the following steps:
- The low pass analog prototype poles, zeros, and gain are calculated.
- The low pass filter is then transformed into the required band pass filter with desired cutoff frequencies.
- Bilinear transformation is used to convert the analog filter to a digital filter.
- The resultant is a transfer function representation of the digital filter.

The results of the simulation are shown below:



FigA2.4: Characteristics of Chebychev filter

The optical Chebychev filter obtained was of order 4. The magnitude plot, shown in the upper right corner of Figure A2.4, represents a 6dB bandwidth estimate of 10 GHz. The ripple in the optical filter pass band will cause the frequencies near the optical cut-off frequency to be distorted. The pass band ripple was seen to be ≤1dB. The magnitude roll off to –40 dB as at 50GHz and to –20dB at 20GHz. This roll-off is fairly crucial to suppress one side band of the RZ signal; the steeper roll shows a favourable characteristic. Further, the phase spectrum of the filter shown in the bottom half of Figure A2.3 again shows linear characteristic of the pass band of the filter. This corresponds to a variable group delay, as shown in the upper right quadrant of Figure A2.4. The corresponding group velocity dispersion plot is shown in the lower left quadrant. The pole zero plot shows all poles inside the unit circle and therefore implies a stable filter. The transfer function is as follows:

$$\frac{2.105\text{x}10^{-12} - 6.315\text{x}10^{-12} z^{-1} + 6.315\text{x}10^{-12} z^{-2} - 2.105\text{x}10^{-12} z^{-3}}{1 + 3.6654x10^{-4} z^{-1} + 3z^{-2} + 7.308x10^{-4} z^{-3} + 2.999z^{-4} + 3.654x10^{-4} z^{-5} + 0.9997z^{-6}} \quad (A23)$$

Each delay unit is considered o be the propagation delay through a thin film layer of a stack of thin film layers forming the optical filter. Thus, the filter is stable when the poles of the z transfer function are close to the unit circle, as shown in the lower right quadrant of Figure A2.4.

13.7 Elliptic Type Band pass filter

This type of filter shows an equi-ripple response in both its pass band and its stop band. These are similar to FIR equi-ripple filters. The magnitude-squared response of the low pass prototype of the order N is given by:

$$\left|H_{LP}(j\omega)\right|^2 = \frac{1}{1 + \varepsilon^2 E^2{}_N(\omega)} \quad (A24)$$

where $E^2{}_N(\omega)$ is called the Chebychev rational function and can be determined from the specified ripple properties. The frequency response is shown in Figure A2.5 below.

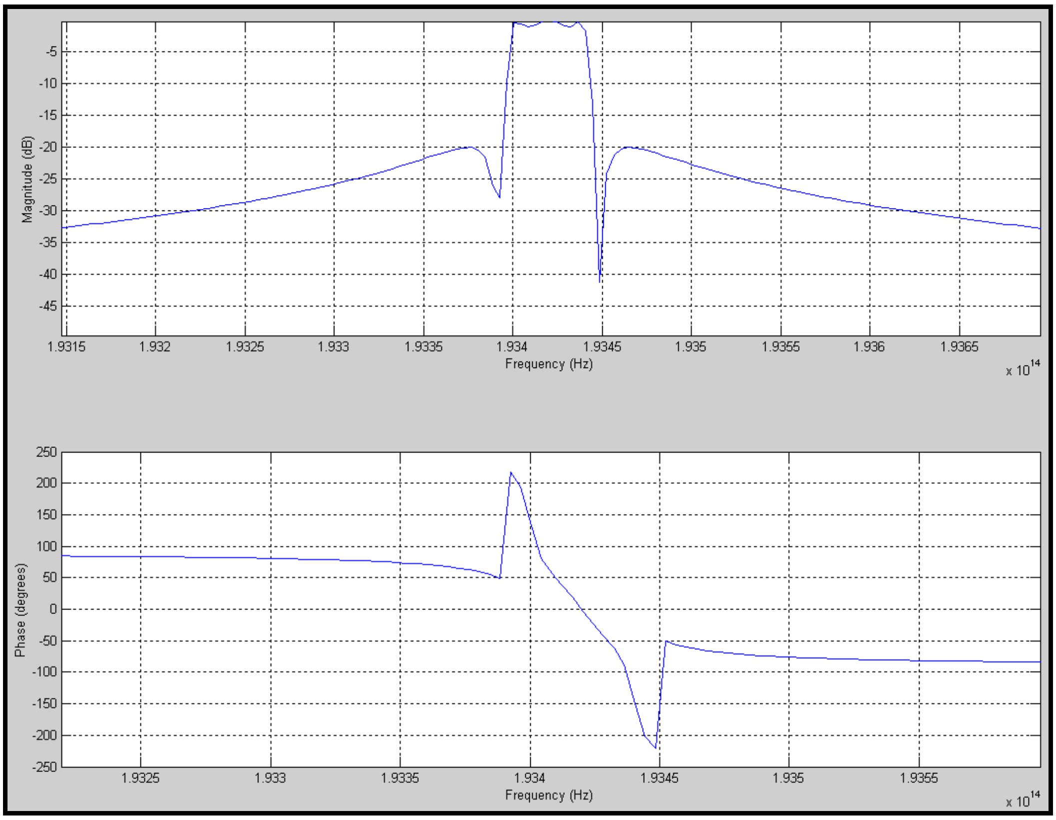


Fig 2.5: Magnitude and phase frequency responses of the elliptic Filter

Again Matlab© is used as the platform for simulation and the algorithm for the calculation follows the following:

- Firstly, the low pass analog prototype poles, zeros, and gain are calculated.
- This low pass filter properties are then converted to the required band pass filter with the desired cut-off optical frequencies.
- For digital filter design, Matlab implements bilinear transformation to convert the analog filter into a digital filter.
- The output is in the form of z-transfer function.

The results of this simulation is shown below

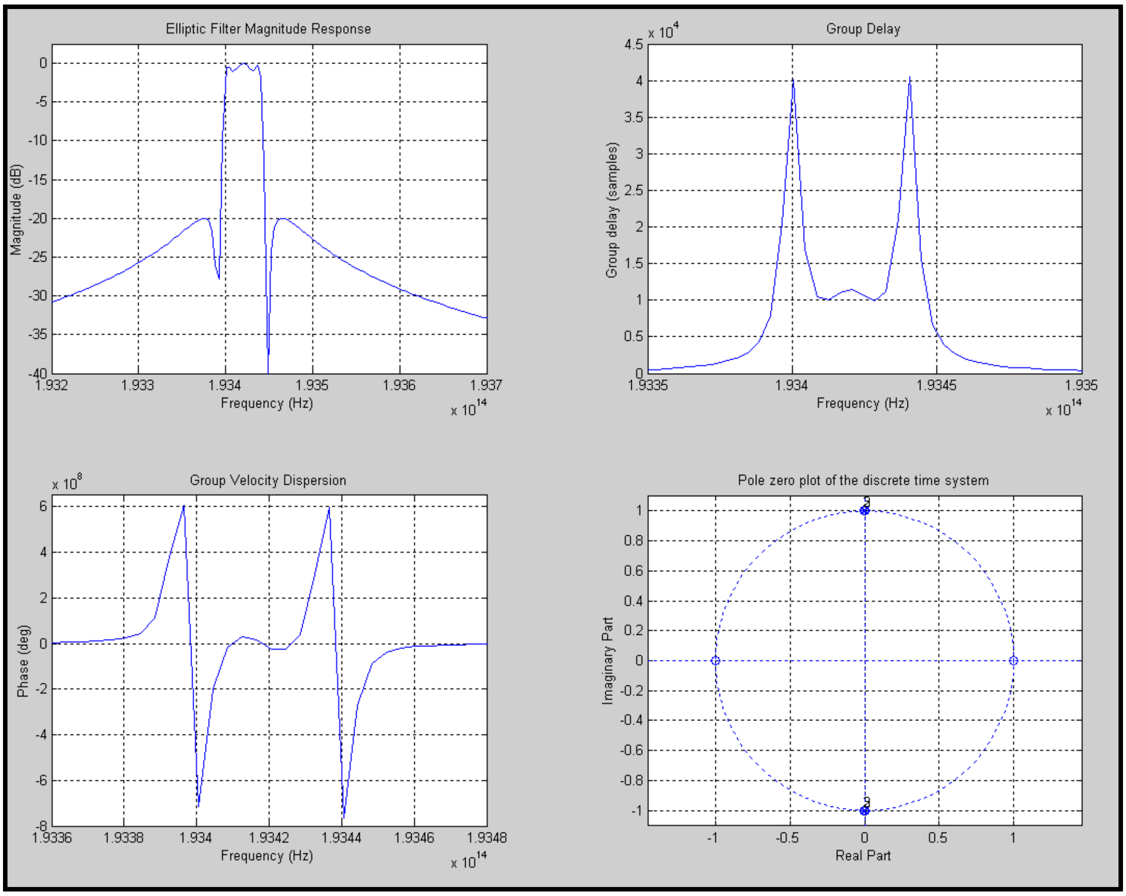


Fig A2.6: Characteristics of Elliptic filter: pass-band, phase and pole-zero pattern in the z-plane.

The magnitude plot, shown in the top left quadrant of Figure A2.6, shows a 6dB bandwidth <10Ghz. The pass band ripple was observed to be ≤1dB. The roll-off to –20db is at 30Ghz which is considered as an important parameter for the suppression of 1 side band of the RZ pulses to obtain the RZ pulses with VSB modulation. The phase plot, seen in the bottom half of figure 2.5, shows a fairly linear phase response over 90% of the pass band. This directly relates to the group delay plot, in the top right quadrant of figure 2.6, which shows a approximately constant group delay in 80 % of the pass band. The corresponding group velocity dispersion plot is shown in the lower right quadrant. Minimum fluctuation in group velocity implies that optical signals passing through the optical filter will suffer minimum delay. The pole-zero plot (lower right quadrant, Figure A2.6) represents that of a stable system, with all poles of the system within the unit circle. The transfer function in discrete z-domain is shown below.

$$\frac{5.206\text{x}10^{-5} + 1.268\text{x}10^{-8} z^{-1} + 5.206\text{x}10^{-5} z^{-2} - 1.271\text{x}10^{-19} z^{-3} - 5.206\text{x}10^{-5} z^{-4} - 1.268x10^{-8} z^{-5} - 5.206\text{x}10^{-5} z^{-6}}{1 + 3.654x10^{-4} z^{-1} + 3z^{-2} + 7.308x10^{-4} z^{-3} + 2.999z^{-4} + 3.654x10^{-4} z^{-5} + z^{-6}} \qquad (A25)$$

13.8 Remarks

This section introduces three most common IIR filters and their implementation in the optical networks. The detailed design process for each optical filter has also been covered. Although the algorithm for computation is more complex for Elliptic than any of the other filters, for common characteristics elliptic filters are optimum. That is to say that they can achieve the minimum order N for the given specifications or achieve the sharpest transition band for a given order N. This is practically proven in the simulations shown in the above sections. For similar effect configurations of Butterworth, Chebychev I and Elliptic filters, these gave filter order of 4,4 and 3 respectively. Another important feature for comparison is the 20dB roll off bandwidth, which follows approximately 30GHz, 20GHz and 10GHz. These and other parameters are tabulated (table1) for comparison purposes. Figure 2.7 shows the resultant magnitude and phase response of the optical elliptic filter.

Characteristic	**Butterworth**	**Chebychev I**	**Elliptic**
Stability	Yes	Yes	Yes
20db roll off BW (GHz)	30	20	10

Table 1: Major Comparison Parameters

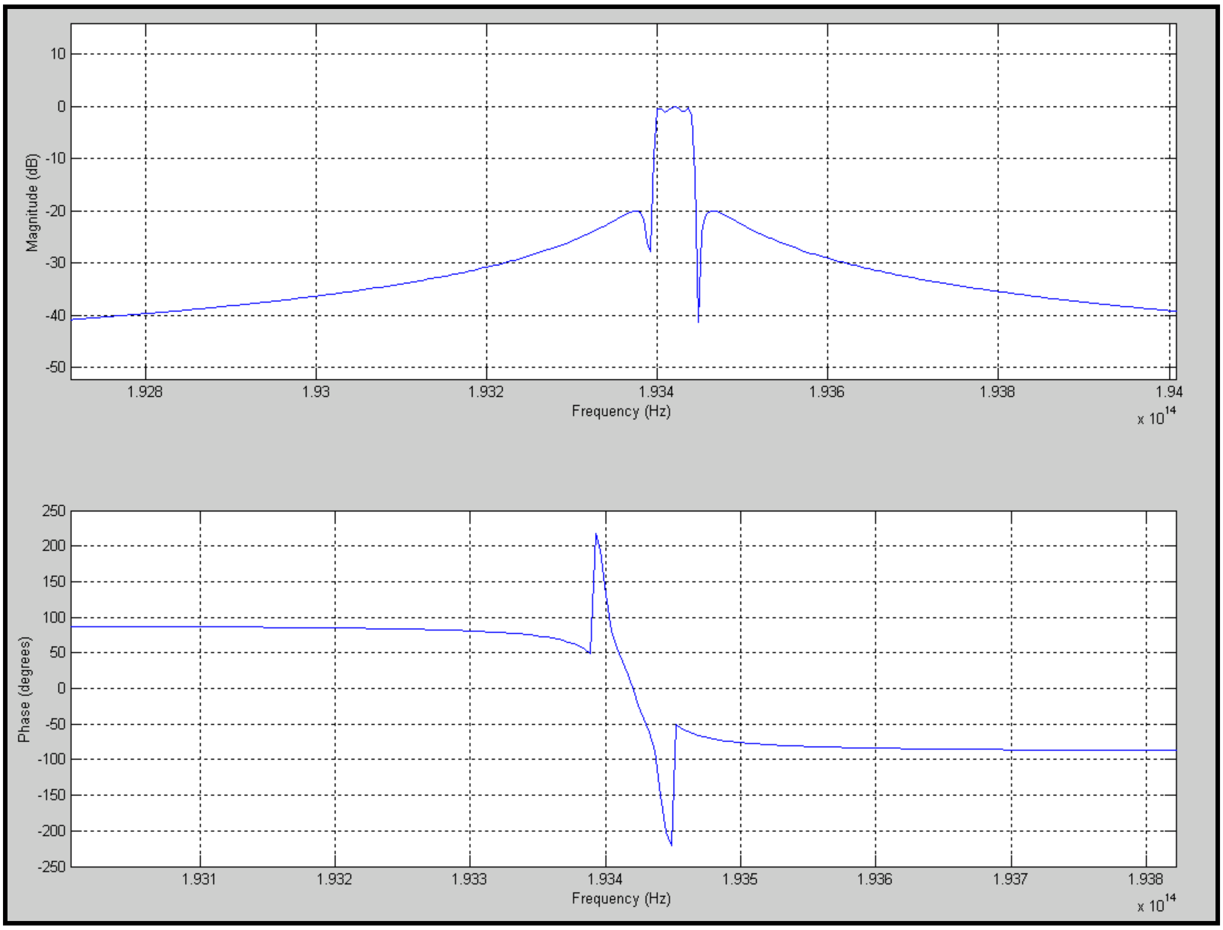


Fig A2.7: Frequency response of the 80GHz elliptic Filter,
20 dB stop band attenuation and 1dB pass-band ripple.

The elliptic filter was chosen to filter out the lower side band of the RZ-DSB signal. The characteristics of the filter can be summarized as follows:

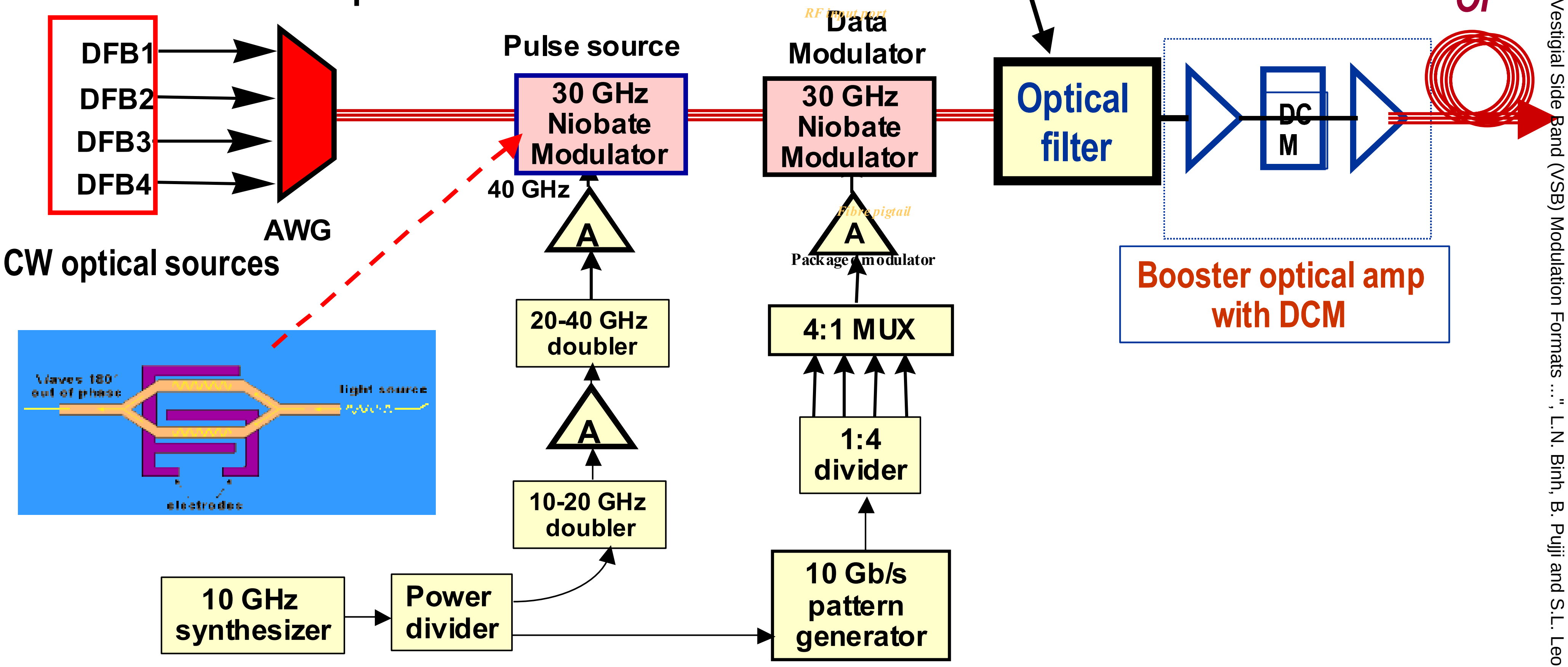
- **Pass Band** (*GHz*) = 40
- **Stop Band** (*GHz*)= 20
- **Pass Band Ripple**, Rp (*dB*) = 1
- **Stop Band Attenuation**, Rs (*dB*) = 20

Order (N) = 3

The optical filter thus designed is then used to obtain the RZ VSB signal, which is ready for propagation. Propagation of the formatted light waves can be modelled by the non-linear Schrödinger equations (NLS). The NLS is solved numerically by the Split Step Fourier method to include both non-linear and dispersive effects As shown in previous section in the main body of the report.

40 Gbit/s RZ-CS Vestigial Single Sideband modulators

- Pulse source modulator driven at 40 GHz
- RZ pulse FWHM ~ 9 ps
- GaAs HEMT multiplexer



MECSE-24-2003 : "Vestigial Side Band (VSB) Modulation Formats ...", L.N. Binh, B. Pujji and S.L. Leong