

Single Mode operation and Transverse Mode control in VCSELs induced by Frequency Selective Feedback

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An experimental study of a *VCSEL* with frequency selective feedback (*FSF*) is reported. We show that we can force the laser to emit in its fundamental transverse mode or in a higher order transverse mode and that we can also control the polarization emitted in the fundamental one. We obtain single fundamental mode operation within a large range of injection current values (almost $\approx 2.5I_{th}$) and a maximum optical power of $2.7mW$. In this current range the output is found to be stable.

I. INTRODUCTION

Vertical Cavity Surface-Emitting Lasers have attracted a great deal of interest in last years for both technological applications and scientific research [1] because of their advantages over edge-emitting lasers (*EEL*): particularly, high modulation bandwidth, circular output beam, low threshold current and single longitudinal mode operation. In fact, due to the short cavity length ($\approx 1\mu m$), *VCSELs* can oscillate in a single longitudinal mode. However, the modal behaviour depends strongly on the transverse dimension of the device, δ , and on the confinement mechanism: in small *VCSELs* ($\delta < 5\mu m$), only the fundamental transverse mode is supported by the cavity, but, due to the small active region, the emitted power is in general quite low. On the other hand, in larger *VCSELs* ($\delta > 5\mu m$) higher optical power can be achieved, but single mode operation is possible only over a limited range of injection currents close to threshold.

Another difference with respect to *EEL* is the polarization behaviour: because of their specific geometry, even in fundamental transverse operation, *VCSELs* can emit two orthogonal polarization modes at the same time or exhibit a flip of the dominant polarization by 90° as the pump current is varied (polarization switching) [2,3]. These two polarization modes are spectrally splitted by a small amount ($\approx 5 - 10GHz$) because of birefringence [4,5].

To obtain high single-mode output power (few mW) within a large range of injection currents could be interesting for spectroscopic applications and (single-mode) communication systems [4,6,7]. For these applications, it is important to avoid multimode oscillation in large aperture devices and to control the polarization of the emitted field. This requires to develop methods for achieving the control of the transverse and polarization modes emitted by the *VCSEL*. Several approaches have been attempted to increase the single mode output power of *VCSELs*: increasing the cavity length [8], hybrid implant/oxide *VCSELs* [9], surface etching [10], passive antiguide region [11]. In [12] the performances of a compact external microcavity surface emitting laser have been studied: $2mW$ single mode emission have been obtained. In [13] the authors demonstrated $4.8mW$ single mode emission, by reducing index guiding on fundamental mode stability. However all these methods involve technical modifications in the structure of the device not available to the common users.

Here, we propose to apply to the *VCSEL* a very standard method to achieve frequency tuning and single longitudinal mode emission in *EEL* [14]. The first order reflection of a diffraction grating used in the grazing incidence configuration (Littman external cavity [15]) is reinjected into the laser cavity by a mirror. In *EEL* the external optical cavity allows to select a single longitudinal mode of the laser because the diffraction grating acts as a frequency selective element while the angle of the tuning mirror selects the output wavelength to reinject. We show that in *VCSELs* this simple setup leads to single fundamental mode emission and that we can control transverse and polarization modes emitted by the device.

II. EXPERIMENTAL SETUP

The experimental setup consists in a *VCSEL* with frequency selective optical feedback through Littman external cavity. The *VCSEL* is a $16\mu m$ diameter oxide-confined device with 33.5 n-type pairs bottom mirror, 26 p-type pairs top mirror, and half-wavelength cavity. The lasing wavelength is $840nm$ at room temperature and the threshold of the solitary laser is $1.60mA$. The external cavity length is $15cm$, corresponding to a free spectral range of $1GHz$. The mode matching condition for the fundamental mode is achieved by focalizing the emitted light on the external cavity mirror. Beam focusing on the external mirror implies that the returned beam at the top mirror is the image of the emitted beam. The output (from the grating zero-order reflection) is sent to a Fabry-Perot interferometer (free spectral range $180GHz$) and, then, is splitted in two parts through a no-polarizing beam splitter: one part is detected by a photodiode providing the optical spectrum, and the other is monitored by a CCD camera providing the corresponding frequency-resolved transverse profiles. Another part of the output beam is detected by an avalanche photodiode (2 GHz bandwidth) coupled with a spectrum analyser, providing information about any presence of fast dynamics in the output. An optical diode is inserted in the path in order to avoid feedback from the Fabry-Perot. A half-wave plate before the grating allows us to change the orientation of the polarization axes of the light with respect to the grating lines. It is worth remarking that the grating efficiency depends on the polarization orientation. The efficiency difference for the two orthogonal polarizations is of a factor 4. In our study we initially fix

the position of the half-wave plate in order to align the polarization axes of the light at 45° with respect to the grating lines. In these conditions, the two orthogonal polarizations emitted by the VCSEL are both oriented at 45° respect to the grating lines and so their losses passing through the grating are the same. As a consequence the percentage of reflected light in the two polarizations is the same. This allows a simpler characterization and interpretation of the results. The threshold reduction is $\approx 4\%$. We have studied the system response as the reinjected frequency is changed (adjusting the tuning mirror angle) and for different values of the pump current: particularly, measures of the optical spectrum and of the frequency resolved transverse profiles are performed.

III. RESULTS AND DISCUSSION

The typical optical spectrum with frequency resolved transverse profile of the solitary laser is shown in Fig. 1. The pump current is 1.70mA . We can clearly see that two polarization in the fundamental mode and higher order transverse modes are emitted. At threshold, the VCSEL emits only in its fundamental transverse mode, but the two orthogonal polarization are involved. At 1.64mA the second order transverse mode starts to emit and at 1.70mA also the third transverse mode is close to threshold. The separation between polarization modes is $\approx 10\text{GHz}$ while between the transverse modes is $\approx 40\text{GHz}$.

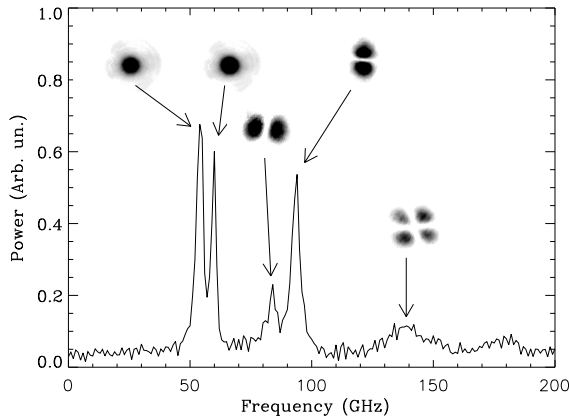


FIG. 1. Solitary laser optical spectrum and frequency resolved transverse profiles at 1.70mA .

In Fig. 2 we show, for the same pump current, the optical spectrum as the reinjected frequency is varied, together the emitted transverse profiles of the VCSEL with FSF in the two polarization.

Several points are worth noting:

1. We can force the laser to emit in any of the two polarization components of the fundamental transverse mode (first and second peak in the figure), in the first transverse mode (third peak) and in the second one (fourth peak). In the solitary laser (see Fig. 1), at this current

we have emission in the fundamental mode and in the first transverse mode, while the second one it is very close to threshold.

2. For perfect mode matched feedback and alignment of the external cavity, no dynamics in the output is observed. In our experiment we have optimized the mode matching for the fundamental mode. As a consequence the mode matching for higher-order transverse modes is not perfect. This fact implies that we can not easily fix the polarization of the higher-order transverse modes, as in the fundamental one, and that the range of parameters (external cavity alignment, current, temperature...) for which the output is stable is smaller than in the case of fundamental mode emission. For instance, the presence of dynamics is evident looking at the width of the fourth peak with respect to the first one, in Fig. 2.
3. When the temperature and the pump current are fixed, the power of each mode selected depends on the feedback strength and on the power of the mode considered, without feedback: in fact, at higher injection currents ($2 - 2.5\text{mA}$) or when the feedback level is higher we are able to excite also the third and fourth transverse mode. However, for currents above 2.5mA , it is difficult to achieve a stable single mode emission.
4. For the above working conditions (same feedback amount in the two polarizations) we obtain a maximum single fundamental mode output power of $\approx 750\ \mu\text{W}$ corresponding to an injection current of 2.5mA .

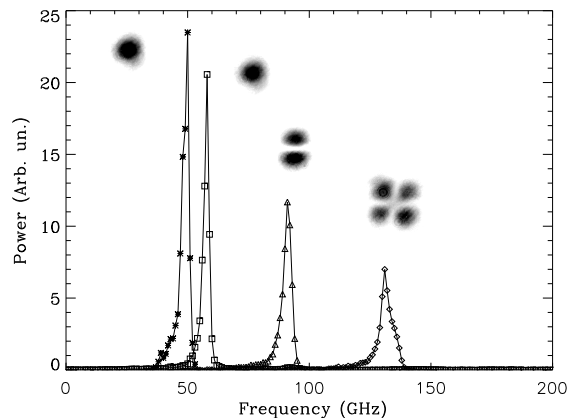


FIG. 2. Optical spectrum and transverse profiles of the VCSEL with frequency selective feedback, as the reinjected frequency is varied: the picture shows the optical spectra corresponding to 4 different tuning mirror angles. The injection current is 1.70mA .

From the point of view of the applications, it could be very important to optimize the single fundamental mode output power and the pump current range of stable single mode operation. For this purpose, we have rotated the half-wave plate (polarization perpendicular to the grating lines) in order to have the strongest feedback as possible. In fact, as mentioned

above, the grating efficiency (and so the feedback level) depends on the polarization. In this case the threshold reduction induced by the optical feedback is $\approx 10\%$.

In these new working condition we select the fundamental transverse mode and we perform a measure as the pump current is varied. During the measure we have to readjust the tuning mirror angle, because of the modal frequency shift due to the current change. The results are shown in Fig. 3. We observe single (fundamental) mode emission until $I \approx 4\text{mA}$ ($\approx 2.5I_{th}$); the corresponding output power is 2.7mW . At this current the output power of the solitary laser is 1.9mW and four transverse modes are emitting. Within this range of currents, the emission is stable and polarized perpendicularly to the grating rulings. For higher injection currents the output starts to loose stability and higher-order transverse modes appear.

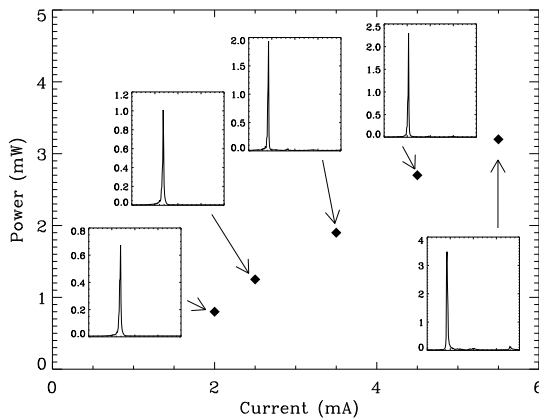


FIG. 3. Optical Spectra and emitted power of the VCSEL with *FSS* in the polarization perpendicular to the grating lines.

IV. CONCLUSION

We have shown experimentally that *FSS* allows us to select transverse modes in *VCSELs* and also to control the polarization in the fundamental one. Due to the dichroic characteristics of the grating, the relative orientation between the polarization components of the VCSEL and the grating rulings plays an important role and allows to select by frequency tuning the fundamental mode in either polarization when equal feedback to both components is applied. When one component is preferentially fed back, the laser output is polarized in this direction, and we have obtained single mode operation in a large range of injection currents with a maximum stable output power of 2.7mW .

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