Numerical analysis of multi-mode VCSELs for applications in high bitrate optical communication

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***Abstract*—We analyze the dynamical behavior of multimode VCSELs with elliptical oxide aperture. An advanced electromagnetic solver is employed to determine the electric field modal thresholds and emission frequencies, while mode competition is simulated with a time-domain mode expansion approach that accounts for coherent effects and carrier-photon spatial coupling. Preliminary performance analysis with NRZ PRBS shows an increase in the modulation bandwidth with respect to the single mode case, allowing for bitrates up to 70 Gbit/s.**

Keywords—VCSEL, semiconductor lasers, multimode dynamics, elliptical aperture

I. Introduction

Short-reach data transmission multimode fiber links often make use of multimode 850 nm VCSELs because they display low threshold current and high power, as required for intra-data center low-cost communication. Standard circular aperture configurations lead to almost degenerate transverse higher order modes, with emission wavelengths separated by a few GHz. While these modes are orthogonal to each other, their beating (mediated by spatial hole burning of carriers in the QWs), is non-null and results in undesired peaks in the relative intensity noise (RIN) spectrum with consequent increase of the RIN integrated over the bandwidth. When increasing the communication bitrate beyond 50 Gbit/s, such noise is detrimental for error-free transmission. In this context, a design of particular interest relies on an elliptical oxide aperture [1,2]: this configuration breaks the degeneracy of the transverse modes and pushes their frequency separation beyond the receiver bandwidth. Unfortunately, when the demand of increasingly higher data rates extends the required bandwidth, the issue of mode beating and the resulting high RIN is bound to emerge again. This work is dedicated to understanding the electromagnetic, static, and dynamical performance of multimode VCSELs with elliptical oxide aperture. To this aim, we have developed a numerical tool that accounts for the coherent coupling of transverse modes in the gain medium. While this tool can be used to predict the RIN and modulation performance of multimode VCSELs, it also allows for deeper understanding of the physics behind the increase of RIN caused by modal beating. As a case study, we investigate a typical multimode VCSEL [1], designed to avoid polarization switching, with an elliptical oxide aperture with ≈80% ellipticity. Electromagnetic simulations demonstrate that by altering the aperture ellipticity, we can tailor the modal thresholds and the frequency separation among different modes. In our design the minimum modal frequency separation is pushed beyond 50 GHz. Preliminary performance analysis with NRZ PRBS signals illustrate the potential suitability of this laser for bitrates up to at least 70 Gbit/s.

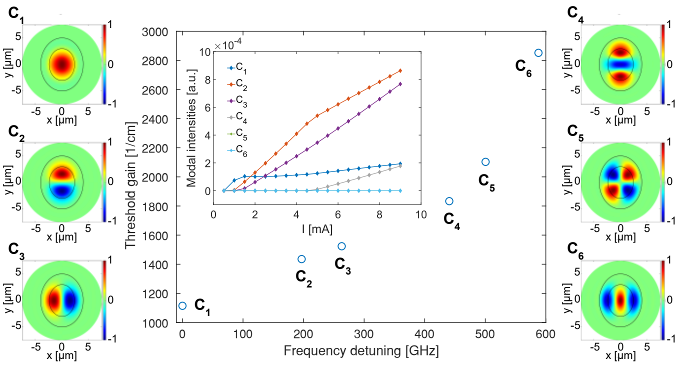

Fig. 1. Threshold gain as a function of the modal frequency detuning with respect to the fundamental mode and respective modal profiles. The inset displays the modal LI curve obtained through dynamical simulations.

II. Modeling and Results

We use our VCSEL electromagnetic (VELM) code as an optical mode solver [3]. This is based on representing the electromagnetic field in terms of cylindrical waves, discriminated by their radial wavevector, field polarization, and azimuthal variation. In this view, VELM is a full-wave vectorial 3D model. In Fig. 1 we report the resulting transverse mode profiles and their respective gain thresholds as a function of the frequency detuning with respect to the lasing frequency of the fundamental mode. Here, we can observe a separation of ≈200 GHz between the fundamental (C_1) and the first higher order mode (C_2) and a separation of >50 GHz between C_2 and C_3. The elliptical shape of the oxide aperture tends to favor, in terms of threshold gain, modal profiles with topographies elongated towards the major elliptical axis: as a

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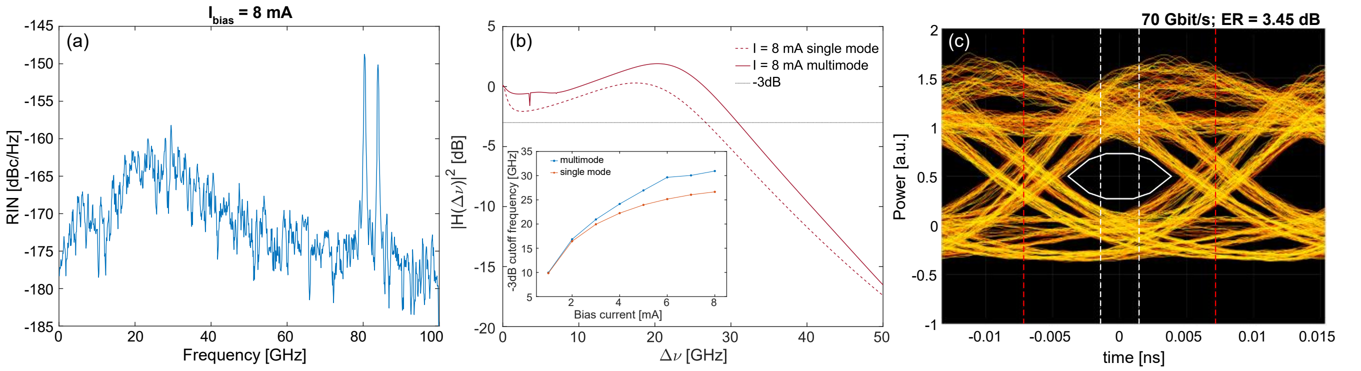

Fig. 2. (a) Spectral RIN and (b) IM response at I_{bias}=8 mA with (b, inset) trend of -3dB cutoff frequency for increasing current. (c) Eye diagram at 70 Gbit/s for average I_{bias}=8 mA.

result, modes with opposite elongations present a higher gain threshold.

The results of the analysis in Fig. 1 are then employed in the dynamical simulator to the aim of analyzing transverse mode competition in presence of coherent frequency mixing effect and spatial hole burning. The simulator is based on the scalar model of [4], modified to include the contribution of carrier diffusion in the transverse plane. The transverse electric field profile $E(\rho,\phi,t)$ is expanded on an orthonormal real basis of Hermite-Gauss modes C_m ($E(\rho,\phi,t) = \sum_m E_m(t)C_m(\rho,\phi)$), while the carrier density in the QWs $N(\rho,\phi,t)$ is expanded on a real basis of Gauss-Laguerre modes B_k [4] ($N(\rho,\phi,t) = \sum_k N_k(t)B_k(\rho,\phi)$). The resulting set of differential equations for the electric field and carrier density modal components is the following:

$$\frac{dE_m(t)}{dt} = \left[i\Delta\omega_m - \frac{1}{2\tau_{p,m}}(1+i\alpha)\right]E_m(t) + \frac{\Gamma G_N}{2}(1+i\alpha)\,f_m(t) + S_{sp}(t)$$

$$\frac{dN_k(t)}{dt} = \frac{\eta_i I_k}{eV} - \frac{N_k}{\tau_e} - \frac{n(0)^2\epsilon_0 G_N}{2\hbar\omega_0} g_k(t) + d_k(t) - 4DN_k(t)q_k$$

with

$$f_m(t) = \int_0^{2\pi} d\phi \int_0^{\infty} \rho\, d\rho \frac{E(\rho,\phi,t)}{1+\varepsilon N_p(\rho,\phi,t)} C_m(\rho,\phi)[N(\rho,\phi,t) - N_0]$$

$$g_k(t) = \int_0^{2\pi} d\phi \int_0^{\infty} \rho\, d\rho \frac{|E(\rho,\phi,t)|^2}{1+\varepsilon N_p(\rho,\phi,t)} B_k(\rho,\phi)[N(\rho,\phi,t) - N_0]$$

$$d_k(t) = 4D\sum_n N_n(t)\left(\int_0^{2\pi} d\phi \int_0^{\infty} \rho\, d\rho\, B_k(\rho,\phi)B_n(\rho,\phi)\rho^2\right)$$

Where $N_p(\rho,\phi,t) \propto |E(\rho,\phi,t)|^2$ is the photon density, ω_0 is the angular frequency of the fundamental mode C_1 (m=1), chosen as reference and $\Delta\omega_m$ is the frequency detuning between mode m and the fundamental mode. The modal photon lifetime is $\tau_{p,m}$, α is the linewidth enhancement factor, Γ is the longitudinal confinement factor, and $G_N = g_N v$ with g_N the differential gain and v the group velocity. Spontaneous emission $S_{sp}(t)$ is modeled as a Langevin stochastic source. The current injection efficiency is η_i and τ_e is the carrier lifetime. I_k are the modal amplitudes on the B_k basis of the bias pump $I(\rho,\phi)$, for which we assume a super-gaussian spatial profile and D is the carrier diffusion coefficient. In the inset of Fig 1, we show the modal LI curves of the simulated multimode 850 nm VCSEL, where each color corresponds to a different transverse mode. For increasing bias currents higher order modes start lasing. In Fig. 2(a) we show the simulated spectral RIN at a bias current of 8 mA. The peaks at about 80 GHz are due to competition between transverse modes. When comparing the IM response in Fig. 2(b) at 8 mA with the respective response obtained by forcing only the fundamental mode to lase, we can observe a clear increase in the modulation bandwidth for the multimode case (see also inset in Fig. 2(b)), which may be seen as an effect of the dynamical competition between modes at higher frequencies. The difference in the -3 dB bandwidth between the single and multimode case grows for increasing currents, where higher order modes reach the lasing threshold.

To test the laser performance for telecom applications, we modulate the bias current to simulate a Non-Return-to-Zero (NRZ) Pseudo-Random Bit Sequence (PRBS) signal at the average current of 8 mA, with upper and lower current levels of 10.6 mA and 5.3 mA, respectively. In Fig. 2(c) we can observe the resulting eye diagram for a bitrate of 70 Gbit/s and $N_{bit}=2^{10}$, displaying an open eye with ≈3.45 dB extinction ratio within the 40%-60% window (within vertical white dashed lines) of a bit period (within vertical red dashed lines). When comparing the eye diagram with the IEEE 802.3ba standard mask for the 40 and 100 Gbit/s transmission systems, we can observe that the eye limits are well respected with this bitrate.

Conclusions

We have studied the properties of a multimode 850nm VCSEL with elliptical aperture. The static emission properties of the device were investigated through an advanced electromagnetic solver, while the laser dynamics were addressed by employing, for one of the first times, a model based on a time domain mode expansion approach that accounts for coherent effects and spatial hole burning. Results have shown a suitability for this laser to increase the modulation bandwidth. Preliminary results on eye diagram analysis for telecom applications have shown acceptable metrics up to 70 Gbit/s.

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