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Dynamical analysis of multimode VCSELs with elliptical oxide aperture

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ABSTRACT

We study the dynamics of a multimode VCSEL with an elliptical oxide aperture for datacom applications. We simulate the laser dynamics through a set of coupled rate equations for the modal components of the electric field and the carrier density, accounting for coherent mode mixing and spatial hole burning. Our simulations show what are the relevant frequency detuning configurations to control in order to improve noise performance. Simulations with NRZ PRBS performed in order to explore the applications of these devices in short-reach data transmission show potentially reachable transmission speeds of 65 Gbit/s.

Keywords: VCSEL, oxide aperture, noise degradation, RIN measurement

1. INTRODUCTION

Multimode 850 nm VCSELs are usually employed in the context of short-reach data transmission multimode fiber links due to their low threshold current, low cost, and high power (with respect e.g., to single mode VCSELs), often required in data centers.[1] While approximately circular aperture configurations are more easily fabricated, they feature almost degenerate transverse higher order modes, with frequency separations of a few GHz. The VCSEL transverse modes are by definition orthogonal: however, while their scalar product is zero, they can present a beating due to their coherent coupling in the gain medium, mediated by carrier spatial hole burning of carriers in the quantum well. This has shown to result in undesired peaks in the relative intensity noise (RIN) spectrum and, consequently an increase in the RIN integrated over a bandwidth. Possible solutions to this problem are considering (i) single-mode VCSEL arrays and (ii) multi-aperture single-mode VCSELs[2,3] in order to obtain a total power comparable with a VCSEL with a larger active area, as well as adopting (iii) different oxide aperture geometries. Among these, the last one is the most mature for the industrial market, especially for employment in data centers. In particular, it can be shown that adopting an elliptical oxide aperture breaks the degeneracy of transverse modes and pushes their frequency separation beyond the expected receiver bandwidth.[4,5] While this efficiently solves the problem at hand, the VCSELs and consequent optical transceivers fabricated today will not necessarily be able to cope with future generation receivers with bandwidths $> 50\,\text{GHz}$, as expected due to the demand for increasingly higher data rates. Therefore, a more in-depth theoretical and numerical study able to address the physical cause behind such noise degradation is mandatory in order to be able to guarantee a lasting datacom infrastructure.

This contribution aims to address the noise performance of multimode 850 nm VCSELs with an elliptical oxide aperture. To this aim, we adopted an electromagnetic optical mode solver[6] to evaluate the relevant laser parameters for dynamical simulations, including the spatial profile of the relevant transverse modes. We then developed a numerical tool accounting for coherent effects in modal competition, spatial hole burning, and carrier diffusion, which is employed to predict RIN and modulation performance of the VCSEL. Our case study consists in a standard multimode elliptical aperture VCSEL with an aspect ratio $\approx 80\%$, designed to avoid polarization

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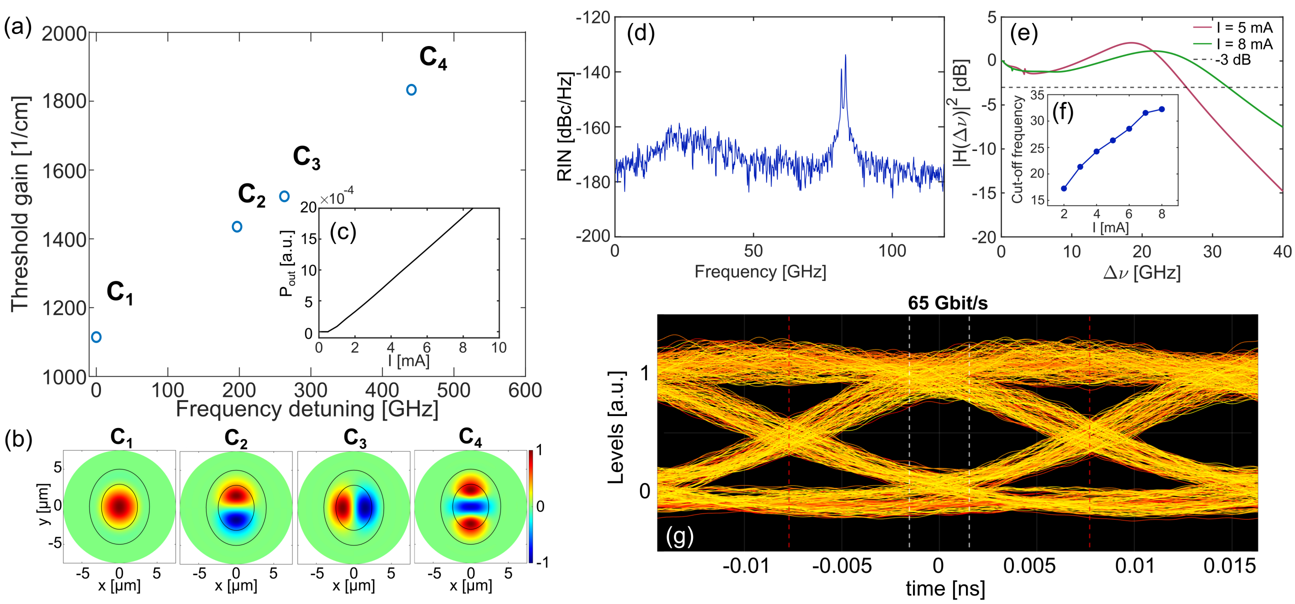

Figure 1. (a) Threshold gain vs modal frequency detuning with respect to the mode C_1 and (b) corresponding modal profiles. (c) Resulting Power-Current characteristic curve. (d) Spectral RIN for $I = 8$ mA. (e) VCSEL IM response at 5 and 8 mA and (f) trend of the -3 dB cut-off frequency for increasing current. (g) Eye diagram obtained through NRZ PRBS modulation at a bitrate of 65 Gbit/s at average current between levels of 8 mA.

switching. We observe that tailoring of modal threshold and frequency separation is made possible by altering the aperture aspect ratio and prove that specific frequency detuning configurations of the modes are the most relevant in designing a VCSEL with optimally low RIN. Current modulation with NRZ PRBS signal results in suitable metrics for datacom up to about 65 Gbit/s.

2. MODELING AND RESULTS

We make use of the VCSEL ElectroMagnetic Suite (VELMS)[6,7] as an optical mode solver, accounting for the detailed structure of a typical multimode VCSEL with an elliptical oxide aperture and an aspect ratio of 80%. As a result, we obtain the threshold modal gain of each mode as a function of its frequency detuning with respect to the fundamental mode, reported in Fig. 1(a). The corresponding transverse spatial profiles for each mode are reported in Fig. 1(b). We observe that the adoption of an elliptical oxide aperture can result in a separation >50 between modes C_2 and C_3, which would have been almost at the same frequency for a circular aperture. These results are employed as input parameters in our dynamical simulator with the scope of studying the effect of modal competition as a result of coherent coupling. Such a simulator is based on the scalar model,[8] which was modified for the inclusion of carrier diffusion in the transverse plane and allows to track the dynamics of each mode C_m through a time-domain mode expansion approach. The model accounts also for spatial hole burning. In particular, the electric field $E(\rho, \phi, t)$, with ρ and ϕ being the polar coordinates in the VCSEL transverse plane, is expanded on the real orthonormal basis of Hermite Gauss modes C_m and the carrier density $N(\rho, \phi, t)$ is expanded on a real basis of Gauss-Laguerre modes B_k,[8] so that

$$E(\rho, \phi, t) = \sum_m E_m(t) C_m(\rho, \phi)\,, \quad N(\rho, \phi, t) = \sum_k N_k(t) B_k(\rho, \phi)\,. \tag{1}$$

As a result, we can simulate the laser dynamics through the following set of differential equations for $E_m(t)$ and $N_k(t)$

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

$$\frac{\mathrm{d}N_k(t)}{\mathrm{d}t} = \frac{\eta_i I_k}{eV} - \frac{N_k(t)}{\tau_e} - \frac{n_g^2 \epsilon_0 G_N}{2\hbar\omega_0} g_k(t) + d_k(t) - 4DN_k(t)q_k \tag{3}$$

with

$$f_m(t) = \int_0^\infty \int_0^{2\pi} \rho \mathrm{d}\rho \mathrm{d}\phi \frac{E(\rho,\phi,t)}{1+\varepsilon N_p(\rho,\phi,t)} C_m(\rho,\phi)\left[N(\rho,\phi,t) - N_0\right] \tag{4}$$

$$g_k(t) = \int_0^\infty \int_0^{2\pi} \rho \mathrm{d}\rho \mathrm{d}\phi \frac{|E(\rho,\phi,t)|^2}{1+\varepsilon N_p(\rho,\phi,t)} B_k(\rho,\phi)\left[N(\rho,\phi,t) - N_0\right] \tag{5}$$

$$d_k(t) = 4D \sum_n N_n(t) \left(\int_0^\infty \int_0^{2\pi} \mathrm{d}\rho \mathrm{d}\phi B_k(\rho,\phi) B_n(\rho,\phi)\rho^3 \right). \tag{6}$$

In Eq. (2), $\Delta\omega_m$ are the modal frequency detunings, as in the x-axis of Fig. 1(a), α is the linewidth enhancement factor, $\tau_{p,m}$ are the modal photon lifetimes, which relate to the y-axis of Fig. 1(a), Γ is the longitudinal confinement factor, G_N is the product of differential gain and group velocity, and S_{sp} is a Langevin stochastic source accounting for spontaneous emission.[9] In Eq. (3), η_i is current injection efficiency and τ_e is the carrier lifetime. I_k are the projection of the (super-Gaussian) current profile on the B_k basis, D is the carrier diffusion coefficient, and q_k is a coefficient related to the mode index.[8] Eq. (4-5) represent the coupling between C_m and other modes and Eq. (6) is due to carrier diffusion. In Fig. 1(c) we report the resulting total power-current characteristic curve, obtained accounting for the contribution of all four modes relevant to the laser dynamics. In Fig. 1(d) we report the resulting simulated spectral RIN at the current of 8 mA. Here, apart from the bump related to relaxation oscillations, we can observe two high peaks at about 80 GHz, which we are due to the coherent coupling between transverse modes. Interestingly, such peaks appear in the RIN only when mode C_4 is above threshold, indicating their origin to be associated to the combination of the frequency detuning of mode C_4 and the higher order harmonics of the frequency separations between the other modes (C_1, C_2, and C_3). While in this example such peaks are beyond the potential receiver bandwidth ($\approx$50 GHz), we highlight that other aperture aspect ratios can lead to RIN peaks within the receiver bandwidth. Further, we observe that other models, not properly accounting for coherent modal coupling, preclude the possibility to observe such peaks in the spectral RIN.[10] Finally, in Fig. 1(e), we illustrate the intensity modulation (IM) response of the laser at 5 and 8 mA. We can observe an increase of the modulation bandwidth for increasing currents of which we report the trend in Fig. 1(f). Focusing on an average current at 8 mA, we modulate the input current via a NRZ PRBS signal at the bitrate of 65 Gbit/s, accounting also for the (standard) equivalent circuit of the VCSEL structure. As a result, we obtain the open eye diagram as illustrated in Fig. 1(g).

3. CONCLUSIONS

We have studied the impact of coherent coupling between transverse modes and spatial hole burning in a 850 nm VCSEL with elliptical oxide aperture and the associated noise performance degradation to the emergence of some specific mode configurations. Preliminary results on current modulation suggest the suitability for datacom application for bitrates up to at least 65 Gbit/s for the device under study.

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