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Physics-oriented model for bow-tie VCSELs

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***Abstract*— Transverse coupled cavity VCSELs promise revolutionary high-speed performance. Significant challenges still persist toward their industrial-level realization, such as temperature stability and manufacturing complexity. Aiming to address these issues, we implemented a physics-oriented rate equation model that offers a comprehensive framework for analysis.**

Keywords—VCSEL, coupled, supermodes, high-speed

I. Introduction

Short-haul intra-datacenter optical communications commonly rely on directly modulated lasers coupled to optical fibers. Targeting high-speed and low power consumption, vertical cavity surface emitting lasers (VCSELs) are currently the leading light source. In this context, the design of high-speed VCSELs is a hot research area, and transverse coupled cavity (TCC)-VCSELs [1] are emerging as a promising candidate for the next generation of devices. These structures, comprising two or more transversely connected cavities, can exhibit extreme intensity modulation (IM) bandwidth performance. Yet, this technology is far from being consolidated at industrial level. To the best of our understanding, this is related to the temperature stability and technological tolerance issues. Addressing such issues requires a solid multiphysics computer-aided design framework. In this view, the models presented in literature so far [2-3] provide a good representation of the physics underlying the bandwidth enhancement. Yet, they lack a straightforward link between the 3-dimensional geometry of the device and the dynamical features, making the analysis of the aforementioned non-idealities a difficult task.

To this end, in [4] we propose a physics-oriented method which is able to extract from our full-wave electromagnetic solver [5] the modal features and translate them into the parameters of a dynamic model. We show that the bandwidth enhancement observed in the TCC-VCSELs can be interpreted as a photon-photon-resonance (PPR) between the supported modes, triggered by the gain profile. Nontrivial effects, such as antiphase oscillations and the need of single-cavity probing, naturally arise in the model. In this work, we apply the method to the structure reported in [6], consisting of two circular oxide apertures linked by a narrow bridge, known as "bow-tie" shapes. In Fig.1, the supported even and odd cold cavity modes (solid lines) are presented together with the bow-tie oxide aperture sketch. The generation of the even and odd supermodes is related to the presence of two identical coupled cavities. For this reason intrinsic technological variations lead to asymmetric modal distributions. In this work, the cavity will be always assumed to be perfectly symmetric, keeping this issue for future investigations. The only assumed asymmetry will instead be introduced by the carrier profile, showing that the presented rate equations result in a modal asymmetry, useful for beam steering applications [7]. Finally, it will be shown how this principle can be used to modulate the PPR intensity, reproducing the observations of [1].

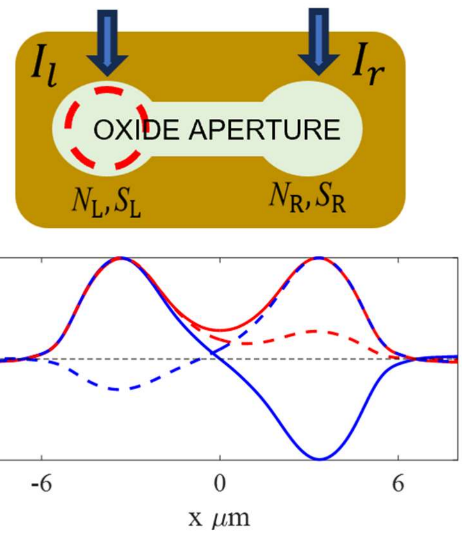

Fig.1 Top: oxide aperture sketch. Bottom: cut of cold cavity modes (solid) and asymmetric cavity modes (dashed) computed with our full-wave electromagnetic solver.

II. Model and Results

By expressing the optical field as a sum of the cold cavity modes, a set of rate equation can be derived from the scalar wave equation [4]:

$$\partial_t E_o = \left(i\Delta\omega - \frac{1}{2\tau_{po}}\right) E_o + k_{oo} E_o + k_{oe} E_e\,, \tag{1}$$

$$\partial_t E_e = -\frac{1}{2\tau_{pe}} E_e + k_{ee} E_e + k_{eo} E_o\,, \tag{2}$$

where the subscripts e and o refer to even and odd mode, τ_p is the photon lifetime, $\Delta\omega$ is the frequency separation and k_{ij} is the following integral on the active region (AR):

$$k_{ij} = \Gamma_z v_g \iint_{AR} \frac{\Psi_i^* \, g\,(N(x,y))\, \Psi_j}{1+\epsilon S(x,y)}\, dxdy \ . \qquad (3)$$

In (3), Ψ_i are the modal envelopes (see Fig. 1), Γ_z is the confinement factor, v_g is the group velocity and $g(N)$ is the spatial gain profile. Equation (3) reveals that the cross interaction is weak when the modes are localized. Assuming the carrier density piecewise constant in the right and left apertures, k_{ij} assume the form of a linear combination of the left and right carrier densities [4]. The system can be therefore closed by two carrier rate equations for the right and left populations:

$$\partial_t N_{l,r} = -\frac{N_{l,r}}{\tau} - \frac{v_g G_d S_{l,r}(N_{l,r}-N_{tr})}{1+\epsilon S_{l,r}} + \frac{q}{V_{l,r}} I_{l,r}\ , \qquad (4)$$

where the subscript l and r refer to the left and right cavity, N is the carrier density, G_d is the active medium differential gain, τ is the carrier lifetime V is the active region volume, N_{tr} is the transparency carrier density, ϵ is the gain compression factor and S is the averaged photon density.

Using the set of parameters from [4], equations (1-4) are solved self-consistently, varying I_r for a fixed I_l = 3 mA and for $\Delta\omega$ = 35GHz. In this case, the continuous wave solution consists of a linear phase-locked combination of the two supermodes:

$$E = (|E_e\,|\Psi_e + |E_o|e^{i\phi}\Psi_o)e^{i\omega t}, \qquad (5)$$

where ω ($\Delta\omega$ order or magnitude) and ϕ are solutions of (1-4). At this point, a small radio frequency signal can be added to I_l to evaluate the dynamics of the system. Fig. 2 shows the IM response obtained by probing solely the left photon density. It can be seen how the PPR intensity can be controlled by varying the right current, reproducing qualitatively the experiment in [1].

In the inset of Fig. 2, the intensity profile, computed as the modulus squared of (5), is modified by the current injection. This asymmetric photon density can be interpreted as a localized hot-cavity mode arising from the carrier-induced gain unbalance. As a preliminary investigation, Fig. 1 (dotted lines) reports the cavity modes assuming a carrier-induced perturbation of Δn=5×10^{-3} shaped as the red dashed circle. In this case an odd-like mode is localized in the unperturbed cavity and an even-like mode is localized in the perturbed one. Finding the hot-cavity modes by full-wave solvers would require a self-consistent carrier-electromagnetics approach like in [8]. In this work instead, the electric field rate equations can be easily coupled with the carrier problem offering a comprehensive and simplified framework. The enhanced IM response of Fig.2 is ultimately interpretable as PPR between the localized hot cavity modes. Its intensity can be controlled by the current unbalance,

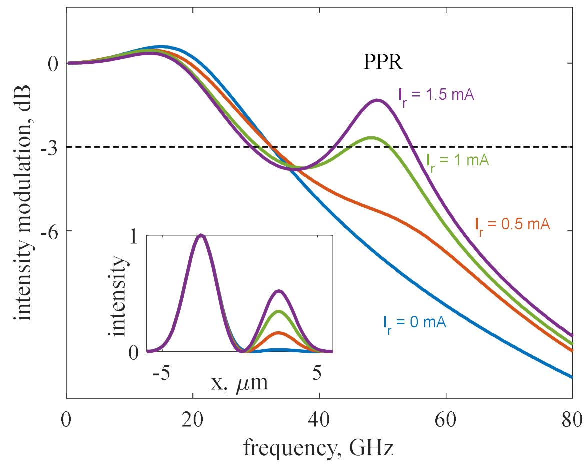

Fig.2 IM response varying I_r. Inset: intensity profile varying I_r.

because the greater the carrier asymmetry the more the modes are localized, making their cross-term interaction (3) smaller.

III. CONCLUSIONS

We reported a physics-oriented approach for the TCC-VCSELs modeling that relates the dynamics features of the device to the modal characteristics. We investigated the asymmetric pumping, showing how the carrier asymmetry leads to modal localization. Due to its compatibility with modal solvers, the presented approach can be readily applied in detailed investigations on technological tolerances and thermal effects, even handling the case of imperfect coupling among the apertures.

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