

Mode-Partition Noise in Vertical-Cavity Surface-Emitting Lasers

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Abstract—We present a numerical study of the effects of carrier diffusion and spatial hole-burning on the noise characteristics of vertical-cavity surface-emitting lasers (VCSEL's) under both single-mode and multimode operations. In the case of single-mode operation, VCSEL noise characteristics are similar to those of edge-emitting lasers except for a diffusion-induced damping of relaxation oscillations. Under multimode operation, VCSEL's exhibit low-frequency noise enhancement due to mode partition. However, depending on the spatial distributions of the transverse modes excited, the mode-partition noise characteristics can be quite different.

Index Terms— Diffusion processes, laser modes, laser noise, semiconductor device noise, surface-emitting lasers.

VERTICAL-CAVITY surface-emitting lasers (VCSEL's) have been studied extensively over the past few years because of their useful characteristics such as a low threshold current, single-longitudinal-mode operation, circular output beam, and wafer-scale integrability [1], [2]. Since VCSEL's are attractive as compact light sources for applications in optical communications and interconnects, it is important to have a thorough understanding of their noise characteristics. Indeed, extensive experimental studies of the intensity-noise in VCSEL's have been performed [3]–[6]. However, theoretical modeling of VCSEL noise have used numerical models which neglect spatial effects [7], [8]. Since VCSEL's have relatively large transverse dimensions, spatial effects are expected to be important, especially because VCSEL's often operate in several transverse modes at high-injection currents [2]. It has been shown that VCSEL's exhibit dynamic and static characteristics significantly different from those of edge-emitting lasers because of spatial hole-burning [9]. Such spatial effects are also expected to affect the VCSEL noise, but have not yet been studied. In this letter, we investigate numerically the mode-partition noise (MPN) of a VCSEL under two-mode operation. The relative intensity noise (RIN) and the frequency-noise spectrum (FNS) are studied using a model which includes the spatial dependence of both the optical field and the carrier density.

Assuming that the VCSEL can operate in several transverse modes simultaneously, the rate equations in the cylindrical

coordinates can be written as [10]

$$\frac{dE_i}{dt} = \frac{1}{2} \{ (1 - i\alpha)G_i(t) - \gamma_i \} E_i + F_i(t), \quad (1)$$

$$\begin{aligned} \frac{\partial N}{\partial t} = & D\nabla_T^2 N + \frac{J(r, \phi)}{qd} - \frac{N}{\tau_e} - BN^2 \\ & - \frac{1}{d} \sum_{i=1}^n G_{\text{local}} |E_i(t)|^2 |\psi_i(r, \phi)|^2 \end{aligned} \quad (2)$$

where $E_i(t)$ is the amplitude of the i th transverse mode with the spatial distribution $\psi_i(r, \phi)$, $N(r, \phi, t)$ is the carrier density, α is the linewidth enhancement factor, and $G_i(t)$ and γ_i are the gain and cavity loss for the i th mode. The modal fields $\psi_i(r, \phi)$ are obtained for the passive index-guided structure and are assumed to remain unaffected by the relatively small carrier-density variations. The effect of spontaneous emission is included by the Langevin noise $F_i(t)$. In (2), τ_e is the carrier lifetime due to nonradiative recombination, D is the diffusion coefficient, B is the spontaneous recombination coefficient, d is the thickness of the active layer, and $J(r, \phi)$ is the injection current density. The local gain $G_{\text{local}} = a_0 v_g (N - N_T)$ is assumed to be linearly proportional to the local carrier density $N(r, \phi, t)$, where N_T is the carrier density at transparency, a_0 is the gain cross section, and v_g is the group velocity. The modal gain $G_i(t)$ for each mode in (1) is obtained by taking into account the spatial overlap between the local-gain profile and the spatial intensity distribution $|\psi_i(r, \phi)|^2$ of that mode.

Equations (1) and (2) are solved numerically by using a finite-difference method with a temporal and spatial resolution of 0.1 ps and 0.1 μm , respectively. The intensity-noise and frequency-noise characteristics are calculated numerically by averaging over 30 trajectories, each of duration 26 ns, resulting in a resolution of 38 MHz over a 20-GHz frequency range. An index-guided VCSEL with cylindrical geometry (index guiding over 4- μm radius) is considered. The active region consists of three 8-nm quantum wells. Relevant device parameters are listed in Table I.

We first consider the case in which the VCSEL operates in a single transverse mode. This behavior can be realized by using a disc contact of 2- μm radius such that current is injected only over a small central part of the VCSEL top surface. The LP₀₁ mode is then preferentially excited. The RIN and FNS are similar to those of edge-emitting lasers and exhibit a resonance peak near 4 GHz corresponding to the relaxation-oscillation frequency. Carrier diffusion is found to affect the RIN and FNS considerably. Our results show a 20%–25% increase in relaxation-oscillation frequency and a reduction by a factor of

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TABLE I
DEVICE PARAMETERS USED IN SIMULATIONS

Cavity length L_{eff}	2 μm
Active-region thickness (3 QWs)	3 \times 8 nm
Radius of device	10 μm
Radius of index-guiding region	4 μm
Diffusion constant D	30 cm^2/s
Nonradiative recombination time τ_e	5 ns
Bimolecular recombination coefficient B	1 $\times 10^{-10}$ cm^3/s
Refractive indices n_1, n_2	3.4, 3.5
Wavelength λ	0.875 μm
Gain cross-section a_0	2.0 $\times 10^{-16}$ cm^2
Group velocity v_g	8.8 $\times 10^9$ cm/s
Carrier density at transparency N_T	2.2 $\times 10^{18}$ cm^{-3}
Linewidth enhancement factor α	3.0
Mirror reflectivities R_1, R_2	0.995
Internal loss α_{int}	20 cm^{-1}
Longitudinal confinement factor Γ_l	0.012

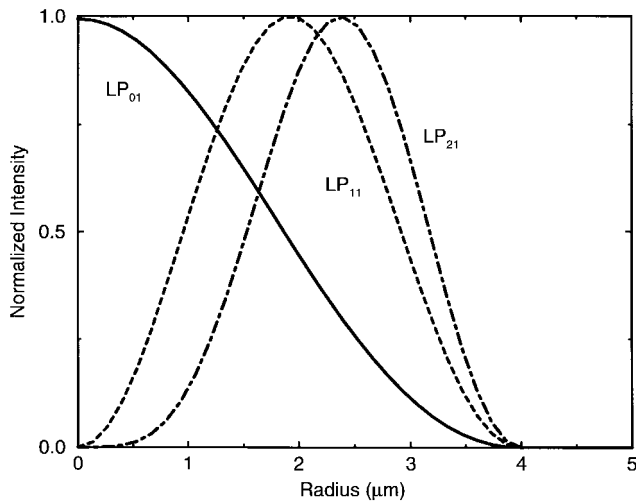


Fig. 1. Radial intensity profiles of the LP₀₁ (solid), LP₁₁ (dashed) and LP₂₁ (dotted-dashed) transverse modes.

5 in the peak height because of carrier diffusion, indicating its beneficial effects in VCSEL's.

We now focus on mode-partition noise by considering the case in which the VCSEL operates in two transverse modes simultaneously. To investigate the effects of different transverse modes, two different contact geometries are considered: a 4- μm radius disc contact which excites the LP₀₁ and LP₁₁ modes, and a ring contact of inner and outer radii of 1.8 and 2.8 μm , which excites the LP₁₁ and LP₂₁ modes. Fig. 1 shows the radial intensity profiles for the three modes.

The smoothed version of the RIN spectra shown in Fig. 2(a) for the case of a ring contact correspond to 8-mA current (two times above threshold for the LP₂₁ mode), for which the powers in the LP₁₁ and LP₂₁ modes are 0.3 and 0.8 mW, respectively. Clearly, power fluctuations in individual transverse modes are larger by up to a factor of 100 (20-dB enhancement) than those of the total power for frequencies up to 4 GHz. This enhancement is known as MPN, and is a consequence of anticorrelated power fluctuations of individual

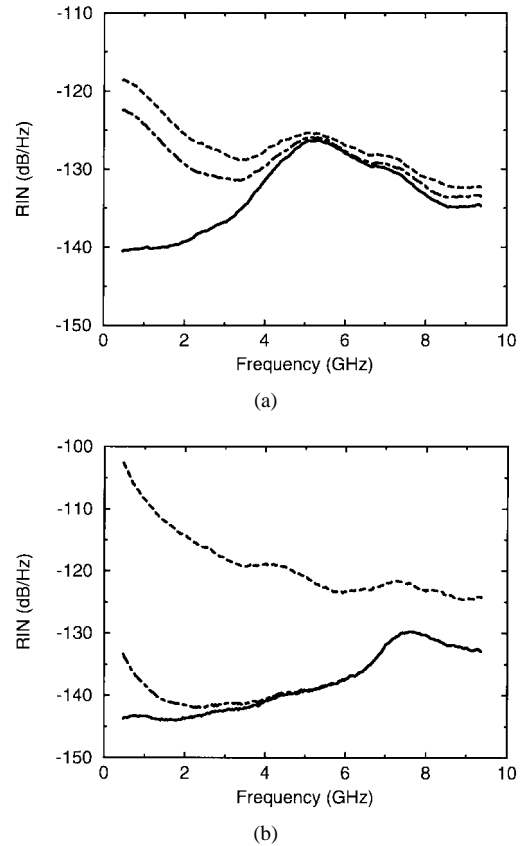


Fig. 2. RIN characteristics for a ring contact with injection current set at (a) two and (b) three times above threshold. Solid, dashed and dot-dashed traces correspond to noise for the total power, the LP₁₁, and LP₂₁ transverse modes, respectively.

modes due to carrier competition [10]. Indeed, MPN has been experimentally observed in both VCSEL's and edge-emitting lasers [4]–[6]. In the case of VCSEL's, transverse effects such as carrier diffusion and spatial hole-burning can affect the MPN dramatically, as will become clear in what follows.

Consider first the impact of the relative powers in each mode on MPN. Since the spatial distributions of the LP₁₁ and LP₂₁ modes overlap significantly, as the current is increased, one mode becomes dominant while the other mode is suppressed due to carrier competition induced by spatial hole-burning [9]. Fig. 2(b) shows the RIN spectra under conditions identical to those of Fig. 2(a) except at three times above threshold, corresponding to powers of 0.1 and 2.7 mW in the LP₁₁ and LP₂₁ modes, respectively. The dominant LP₂₁ mode exhibits noise enhancement over a smaller frequency range (0–1 GHz).

To further investigate the effect of spatial hole-burning, the RIN spectra for the case of a disc contact (4- μm radius) are shown in Fig. 3. The current is two times above threshold for the LP₀₁ mode and the mode powers are nearly equal (about 0.7 mW). The low-frequency enhancement of RIN for individual modes is reduced by a factor of 10 compared with the case shown in Fig. 2(a), even though the VCSEL operates in two modes in both cases. The same device parameters are used, except for a disc contact which excites the LP₀₁ and LP₁₁ modes while the ring contact excites the LP₁₁ and LP₂₁ modes. These results can be understood from the mode

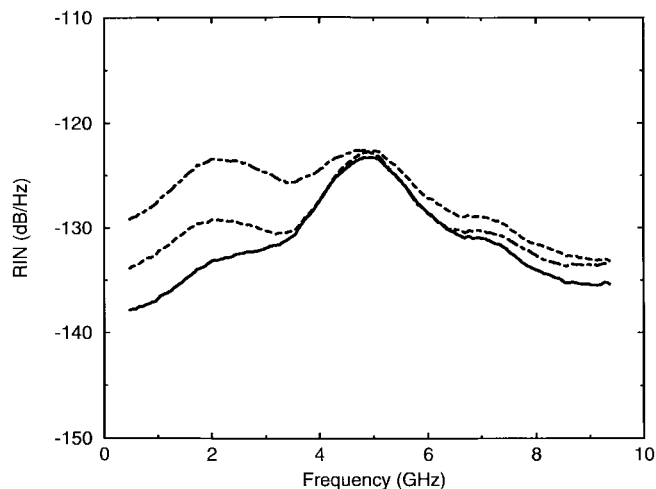


Fig. 3. RIN characteristics for a $4\text{-}\mu\text{m}$ -radius disc contact with injection current set at two times above the threshold. Solid, dashed and dotted-dashed traces correspond to noise for the total power, the LP_{01} and the LP_{11} transverse modes, respectively.

profiles shown in Fig. 1. The LP_{01} and LP_{11} modes have a smaller region of overlap, carrier competition is less intense for a disc contact, despite the fact that the two modes carry the same amount of power. At three times above threshold, MPN is found to be reduced so much that the low-frequency noise is lower than that occurring at the relaxation-oscillation peak. Thus, contrary to relatively high MPN in edge-emitting lasers operating in several longitudinal modes, but in a single-transverse mode, multitransverse-mode VCSEL's can be made with reduced MPN through the use of an appropriate pumping geometry.

An interesting feature of Fig. 3 is the appearance of a second peak near 2 GHz in addition to the relaxation-oscillation peak at 4.5 GHz. Such a peak has never been observed in the RIN spectra of edge-emitting lasers, and its presence is solely due to multiple transverse modes. Its absence in Fig. 2 suggests that its origin lies in the disc-contact geometry. The LP_{01} and LP_{11} modes excited in such a VCSEL peak at $r = 0$ and $r \approx 2\ \mu\text{m}$, as seen in Fig. 1. In contrast, the ring-contact geometry excites the LP_{11} and LP_{21} modes, both of which peak near $r = 2\ \mu\text{m}$. Spatial hole-burning burns a hole in the carrier-density profile at the location where the mode intensity peaks. Clearly, two distinct spatial holes are burnt in the case of Fig. 2, whereas

a single hole is burnt in the case of Fig. 3. As a result, carrier diffusion is much more effective in filling the spatial holes (and therefore reducing mode competition) in the case of a disc contact. For a diffusion constant of $30\ \text{cm}^2/\text{s}$ and a carrier recombination time of $\tau \approx 3\ \text{ns}$, the effective diffusion rate is estimated to be about 2–3 GHz. Therefore, RIN enhancement is reduced due to diffusion effects for frequencies below 2 GHz, but not in the frequency range 2–4 GHz, resulting in a shallow peak near 2 GHz. The inclusion of nonlinear gain reduces the peak values in Figs. 2 and 3 by about 2 dB, but the qualitative behavior remains unaffected.

In conclusion, we have investigated the effects of different transverse modes on mode-partition noise in VCSEL's by using different contact geometries. For a ring contact, MPN similar to that of edge-emitting lasers is observed. In contrast, for a wide disc contact, MPN is significantly reduced because of reduced carrier competition, resulting from a smaller spatial overlap of the two transverse modes excited.

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