

Transient Response of ARROW VCSELs Under External Optical Feedback

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Abstract—The effect of external optical feedback on the transient response of antiresonant reflecting optical waveguide (ARROW) vertical-cavity surface-emitting lasers (VCSELs) is studied. It can be shown that the proper design of ARROW can suppress the excitation of high-order transverse leaky mode as well as increase the critical feedback strength so that stable high-power single-mode operation of VCSELs can be obtained even under the influence of strong external optical feedback.

Index Terms—Antiresonant reflecting optical waveguide (ARROW), multitransverse modes, optical feedback, vertical-cavity surface-emitting lasers (VCSELs).

I. INTRODUCTION

ANTIRESONANT reflecting optical waveguides (ARROWS) have been employed to improve high-power single-mode operation in vertical-cavity surface-emitting lasers (VCSELs) [1]. Studies have shown that ARROWS can be used to suppress high-order transverse leaky mode [2], [3], control modal polarization [4], and eliminate secondary pulsation in VCSELs. On the other hand, it is believed that the large radiation loss margin of ARROWS can also be used to minimize the effects of optical feedback on the transverse leaky-mode selection [3]. In addition, the reduction of photon lifetime in VCSELs (by increasing the radiation loss of ARROW) without sacrificing the high reflectivity of distributed Bragg reflectors (DBRs) may reduce the sensitivity of VCSELs to optical feedback [5]. However, these characteristics of ARROW VCSELs have not been explored. In this letter, the capability of using ARROW to achieve stable high-power single-mode operation in VCSELs under the influence of external optical feedback is investigated.

II. NUMERICAL SIMULATIONS

The schematic of an ARROW VCSEL with an external optical reflector is given in Fig. 1. It is assumed that the ARROW has a low-index core region of diameter d_1 which is surrounded by two cladding layers of thickness s (first cladding layer) and d_2 (second cladding layer). The refractive indexes of the core (n_1), first (n_2), second (n_3), and the outer cladding layers (n_4) are 3.3, 3.35, 3.3, and 3.35, respectively. The external reflector is located at some distance away from the p-DBR. The free-space lasing wavelength is assumed to be $0.98 \mu\text{m}$. Two transverse leaky modes (i.e., LM_{01} and LM_{11} , where LM denotes leaky

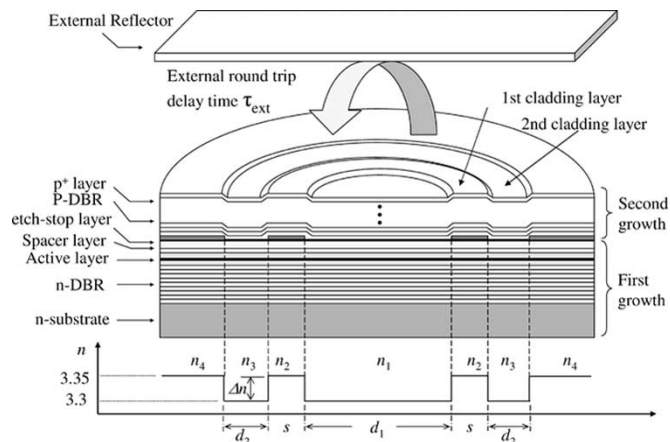


Fig. 1. Schematic of an ARROW VCSEL under the influence of external optical feedback.

modes), which have the lowest radiation losses, are only considered in this investigation. This is because the radiation losses of other higher transverse leaky modes are much higher than that of LM_{01} and LM_{11} in ARROW [6].

The rate equations of photon density S_m and phase ϕ_m which take into consideration of external optical feedback, can be written as

$$\frac{\partial S_m}{\partial t} = v_g (\Gamma_z \langle g_m \rangle - \alpha_m - \zeta_m) S_m + \beta_{sp} \Gamma_z B_{sp} \langle N \rangle^2 + \text{Ref}_{S,m}(t), \quad (1)$$

$$\frac{\partial \phi_m}{\partial t} = \frac{1}{2} \alpha_H v_g \Gamma_z [\langle g_m \rangle - \langle g_{th,m} \rangle] + \text{Ref}_{\phi,m}(t) \quad (2)$$

where the subscript $m = 0$ and 1 represent LM_{01} and LM_{11} , respectively, and $\langle \rangle$ is the spatial average. N is the carrier concentration, $\Gamma_z (= 0.06)$ is the longitudinal confinement factor, $v_g (= 83.3 \times 10^8 \text{ cm/s})$ is the group velocity, $B_{sp} (= 1 \times 10^{-10} \text{ cm}^3/\text{s})$ is the bimolecular recombination coefficient, $\alpha_H (= 4.8)$ is the linewidth enhancement factor, $\beta_{sp} (= 1 \times 10^{-5})$ is the spontaneous emission factor, and $\zeta_m (= 50 \text{ cm}^{-1})$ is the total cavity loss. g_m is the optical gain, $g_{th,m}$ is the threshold gain [5], and α_m is the radiation loss [6]. The optical feedback of photon density $\text{Ref}_{S,m}$ and phase $\text{Ref}_{\phi,m}$ can be written as

$$\text{Ref}_{S,m}(t) = k_{\text{ext}} \tau_L^{-1} \sqrt{S_m(t) S_m(t - \tau_{\text{ext}})} \cos(\theta_m(t)) \quad (3)$$

$$\text{Ref}_{\phi,m}(t) = -k_{\text{ext}} \tau_L^{-1} \sqrt{\frac{S_m(t - \tau_{\text{ext}})}{S_m(t)}} \sin(\theta_m(t)) \quad (4)$$

where $\theta_m(t) = \phi_m(t) - \phi_m(t - \tau_{\text{ext}}) + \omega_{\text{th}} \tau_{\text{ext}}$, ω_{th} is the oscillation frequency at threshold, τ_{ext} is the external round

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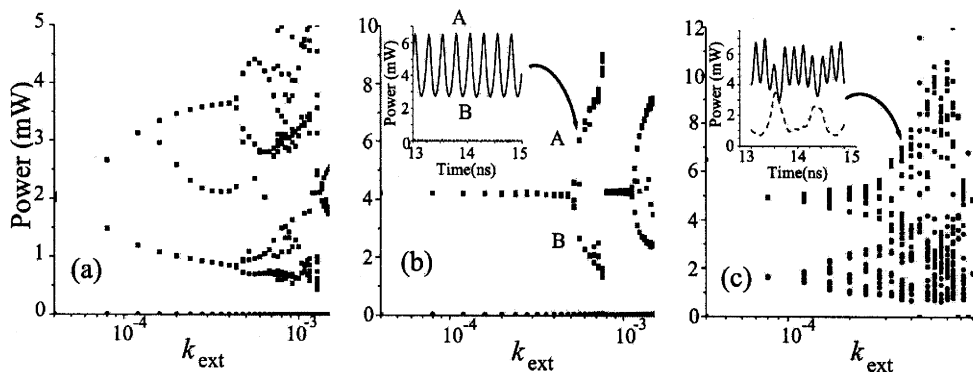


Fig. 2. Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELS with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, and $d_2 = 6 \mu\text{m}$ when injection current density is (a) 6.5, (b) 7, and (c) 8.5 kA/cm². ■: LM₀₁. •: LM₁₁. The inserts give the transient response of LM₀₁ (solid line) and LM₁₁ (dashed line) over a time period of 2 ns.

trip delay time, and τ_L ($= 0.15 \text{ ps}$) is the round-trip time inside the laser cavity. The feedback parameter k_{ext} is defined as $k_{\text{ext}} = \eta(1 - R_1)\sqrt{R_{\text{ext}}}/\sqrt{R_1}$, where R_{ext} is the external reflectivity, R_1 ($= 0.997$) is the reflectivity of DBRs, and η ($= 0.4$) is the coupling between the external mirror and laser. If R_{ext} is set to 0.1, the corresponding value of k_{ext} is about 3.8×10^{-4} . It is noted that short-distance reflection has less influence on the transient response of VCSELS [7]. Hence, only long-distance reflection ($\tau_{\text{ext}} = 0.23 \text{ ns}$) is considered in our analysis. The rate equation of the carrier concentration used in this investigation can be found in [8]. A transparent electrode, which is used to inject current into the active layer, has a diameter of d_1 and is located on top of the p-DBR. The injection current density is described by [8, eq. (5)] with r_o set to $1.5 \mu\text{m}$ to estimate the diffusion of injection current inside the p-DBR. The photon density and carrier concentration of the ARROW VCSEL under the influence of external optical feedback are solved self-consistently.

The influence of radiation loss on the sensitivity of VCSELS to the optical feedback can be explained by the critical feedback strength k_{crit} , which is defined as the minimum reflectivity to force the laser into coherence collapse regime. k_{crit} can be expressed as $k_{\text{crit}} = \tau_L\sqrt{2\omega_r}/\sqrt{1 + \alpha_H}$, where $\omega_r = \nu_g(\alpha_m + \zeta_m)S_m\partial g_m/\partial N$ is the relaxation oscillation frequency and $\partial g_m/\partial N$ is the differential gain coefficient [9]. This implies that under the influence of external optical feedback, stable transient response of ARROW VCSELS can be enhanced if the value of α_m is increased.

Two possible designs of ARROWS have been proposed to improve the performance of VCSELS: ARROWS are optimized for 1) minimum threshold current [1], [2], and 2) maximum radiation loss margin (i.e., radiation loss difference between LM₀₁ and LM₁₁) [3], [4] of VCSELS. The former (latter) approach will minimize (increase) the radiation loss of LM₀₁. Under the influence of external optical feedback, it is foreseen that the transient response of the two designs will exhibit differently due to the difference in radiation loss margin and k_{crit} (i.e., radiation loss of LM₀₁). This can be demonstrated by first studying a 12- μm core diameter VCSEL with the design of ARROW for minimum threshold current. The corresponding values of s and d_2 are selected to be 2.4 and 6 μm , respectively, and the radiation loss of LM₀₁ is minimized to $\alpha_1 = 0.38 \text{ cm}^{-1}$. The bifurcation

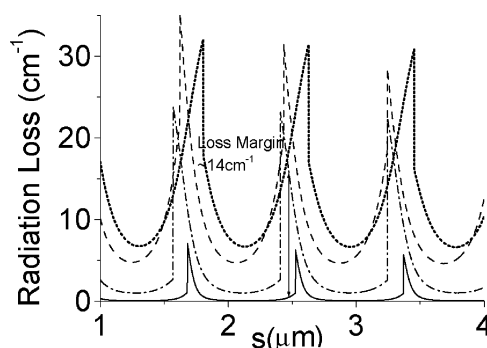


Fig. 3. Radiation loss of the four lowest loss leaky modes plotted versus s with $d_2 = 3.9 \mu\text{m}$. Solid line: LM₀₁. Dashed-dotted line: LM₁₁. Dashed line: LM₁₂. Dotted line: LM₂₂.

diagrams are given in Fig. 2 for the laser with an injection current of (a) 6.5 kA/cm² (only LM₀₁ is excited), (b) 7 kA/cm² (threshold of LM₁₁), and (c) 8.5 kA/cm² (both LM₀₁ and LM₁₁ are excited). In case Fig. 2(a), it is observed that LM₁₁ is completely suppressed due to the design of ARROW. However, due to low output power and a small value of α_1 , the resulting value of k_{crit} is small, such that LM₀₁ exhibits period-doubling route to chaos. In case Fig. 2(b), the increase in output power increases the value of k_{crit} resulting in the laser to be less sensitive to optical feedback. In case Fig. 2(c), further increase in injection current excites LM₁₁, due to spatial-hole-burning of the carrier concentration [3], which triggers the unstable operation of VCSELS under external optical feedback.

Fig. 3 plots the radiation losses versus s for the four lowest transverse leaky modes (i.e., LM₀₁, LM₁₁, LM₁₂, and LM₂₂) of ARROW with configuration of $d_1 = 12 \mu\text{m}$ and $d_2 = 3.9 \mu\text{m}$. The circle shows the choice of $s = 2.46 \mu\text{m}$ for the design of maximum radiation loss margin [3], [4] but the corresponding radiation loss of LM₀₁ has increased to $\alpha_1 = 0.49 \text{ cm}^{-1}$. The corresponding bifurcation diagrams for the ARROW VCSELS are given in Fig. 4. Three bias current densities are chosen so that the corresponding total output intensities (with $k_{\text{ext}} = 0$) of the VCSELS are about the same as that given in Fig. 2. It is observed that LM₁₁ is completely suppressed in the entire range of injection current due to the large radiation loss margin. Furthermore, LM₀₁ exhibits lesser sensitivity to optical feedback than that of Fig. 2. These observations are expected because 1) large

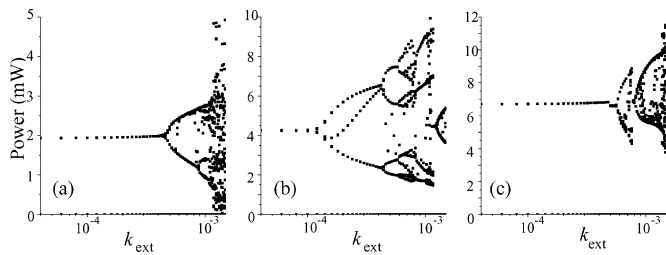


Fig. 4. Bifurcation diagrams with respect to the feedback parameter k_{ext} for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, and $d_2 = 3.9 \mu\text{m}$ when injection current density is (a) 5.82, (b) 6.42, and (c) 7.22 kA/cm^2 . ■: LM_{01} . ●: LM_{11} .

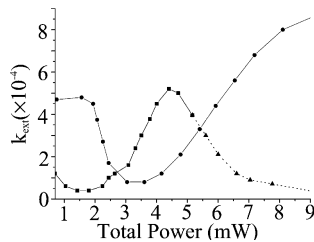


Fig. 5. Plot of maximum k_{ext} versus total output power for the ARROW VCSELs with $d_1 = 12 \mu\text{m}$, $s = 2.4 \mu\text{m}$, $d_2 = 6 \mu\text{m}$ (■: minimum threshold current) and that with $d_1 = 12 \mu\text{m}$, $s = 2.46 \mu\text{m}$, $d_2 = 3.9 \mu\text{m}$ (●: maximum radiation loss margin).

radiation loss margin suppresses the excitation of LM_{11} at high bias and 2) large value of α_1 minimizes the sensitivity of LM_{01} to optical feedback at low bias. As a result, the influence of external optical feedback leading to higher order bifurcations and chaos is minimized. Fig. 5 delineates the sensitivity of LM_{01} to optical feedback for the two ARROW designs. The vertical axis of Fig. 5 records the maximum value of k_{ext} at which stable single-mode operation can still be maintained. It is shown that the design of ARROW VCSELs with maximum radiation loss margin has stable high-power single-mode operation even under strong optical feedback.

The increase in threshold current density J_{th} , due to the increase of α_m , can be estimated $J_{\text{th}} \approx J_o \exp((\alpha_m + \zeta_m)/\Gamma_z a_N)$, where J_o is a proportional constant and $a_N (= 1.5 \times 10^3 \text{ cm}^{-1})$ is the gain coefficient. Hence, if α_m increases from 0.38 to 0.49 cm^{-1} , J_{th} will only increase by not more than 0.5%. In fact, our numerical calculation has verified that the increase in J_{th} will not be more than 5%. The differential quantum efficiency η_d can be

approximated by $\eta_d \approx \zeta_m/(\alpha_m + \zeta_m)$. Hence, the reduction of η_d will be less than 0.5% if α_m increases from 0.38 to 0.49 cm^{-1} . The fabrication tolerance is also studied. It can be shown that the insensitivity to external optical feedback can be maintained if the uncertainty of s and d_2 is less than ± 0.15 and $\pm 0.25 \mu\text{m}$, respectively, from the optimum position. In addition, the variation of $\Delta n (= n_2 - n_1)$ should be less than 5%.

III. CONCLUSION

The capability of using ARROWs to suppress higher order bifurcations and chaos in VCSELs is studied. It is found that the design of ARROW with maximum radiation loss margin can stabilize high-power single-mode operation of VCSELs under the influence of strong external optical feedback. This is because large radiation loss margin suppresses the excitation of LM_{11} at high output powers such that the influence of LM_{11} on the stability of LM_{01} is minimized. In addition, the increase in radiation loss of LM_{01} (i.e., increase in k_{crit}) reduces the sensitivity to optical feedback thereby delaying the onset of chaos.

REFERENCES

- [1] D. Zhou and L. J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers," *IEEE J. Quantum Electron.*, vol. 38, pp. 1599–1606, Dec. 2002.
- [2] T. W. Lee, S. C. Hagness, D. Zhou, and L. J. Mawst, "Modal characteristics of ARROW-type vertical cavity surface emitting lasers," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 770–772, Aug. 2001.
- [3] C. W. Tee and S. F. Yu, "Design and analysis of cylindrical antiresonant reflecting optical waveguide," *J. Lightwave Technol.*, vol. 21, pp. 3379–3386, Dec. 2003.
- [4] N. S. Chen, S. F. Yu, and C. W. Tee, "Suppression of polarization switching in birefringent antiresonant reflecting optical waveguide vertical-cavity surface-emitting lasers," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 711–713, Mar. 2004.
- [5] S. F. Yu, "Nonlinear dynamics of vertical cavity surface emitting lasers," *IEEE J. Quantum Electron.*, vol. 35, pp. 332–341, Mar. 1999.
- [6] C. W. Tee, C. C. Tan, and S. F. Yu, "Design of antiresonant reflecting optical waveguide-type vertical cavity surface emitting lasers using transfer matrix method," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1231–1233, Sept. 2003.
- [7] J. Y. Law and G. P. Agrawal, "Effects of optical feedback on static and dynamic characteristics of vertical-cavity surface-emitting lasers," *IEEE J. Select. Topics Quantum Electron.*, vol. 3, pp. 353–358, Apr. 1997.
- [8] S. F. Yu, "Polarization selection in birefringent antiresonant reflecting optical waveguide-type vertical cavity surface emitting lasers," *IEEE J. Quantum Electron.*, vol. 39, pp. 1362–1372, Nov. 2003.
- [9] L. N. Langley and K. A. Shore, "Effect of optical feedback on the noise properties of vertical cavity surface emitting lasers," *Proc. Inst. Elect. Eng. (Optoelectron.)*, vol. 144, no. 1, pp. 34–38, 1997.