Suppression of Polarization Switching in Birefringent Antiresonant Reflecting Optical Waveguide Vertical-Cavity Surface-Emitting Lasers

N. S. Chen, S. F. Yu, *Senior Member, IEEE*, and C. W. Tee

***Abstract*—Influence of birefringence on the multimode operation of antiresonant reflecting optical waveguide (ARROW) vertical-cavity surface-emitting lasers (VCSELs) is analyzed. It can be shown that polarization switching is mainly due to thermal lensing effects. Hence, a new design rule is proposed to optimize the dimensions of ARROW for the suppression of polarization switching. Using the optimized design, the maximum single-polarization output power of VCSELs can be tripled. In addition, it is shown that the performance of the optimized ARROW VCSELs will not be deteriorated by the uncertainty of birefringence.**

***Index Terms*—Antiresonant reflecting optical waveguide (ARROW), birefringence, multitransverse modes, polarization switching, semiconductor laser modeling, spatial hole burning (SHB), thermal lensing effects, vertical-cavity surface-emitting lasers (VCSELs).**

I. INTRODUCTION

IN LARGE aperture antiresonant reflecting optical waveguide (ARROW) vertical-cavity surface-emitting lasers (VCSELs), birefringence can arise from the less controllable anisotropic strain/stress inside the dielectric multilayered structure [1] so that polarization switching will occur under the influence of spatial hole burning (SHB) and thermal lensing effects [2]. Therefore, it is necessary to optimize the ARROW structure in order to sustain high-power single-polarization operation. Recently, cold-cavity simulations have been developed to optimize ARROW VCSELs for high-power single-mode operation [3], [4]. However, a detailed analysis on the above-threshold multimode characteristics of ARROW VCSELs is lacking. In addition, the capability of using ARROW to suppress polarization switching has not been explored. In this letter, the multimode characteristics of ARROW VCSELs are studied. A new design rule is also proposed to design ARROW VCSELs for high-power single-polarization operation. Furthermore, it can be shown that the performance of the optimized ARROW VCSEL is robust to the uncertainty of birefringence.

II. NUMERICAL SIMULATIONS

Fig. 1 shows the schematic of an ARROW VCSEL used in our analysis. The low index core region (with diameter $d_1 = 12\ \mu$m) is surrounded by two reflectors, which are the first and second cladding layers, with thickness of s and d_2, respectively. In the absence of birefringence, the refractive indexes of the core, first, second, and the outer cladding layers are equal to $n_1 = 3.3$, $n_2 = 3.35$, $n_3 = 3.3$, and $n_4 = 3.35$, respectively. Only two transverse leaky modes (i.e., LM_{01} and LM_{11}, where LM stands for leaky mode) with the lowest radiation losses are considered in our studies. This is because the other transverse leaky modes have radiation losses of at least 5 cm^{-1} higher than that of LM_{11} in the ARROW structures under investigation. Furthermore, each transverse leaky mode is assumed to have a cosine and sine azimuthal dependence due to the axis-symmetric geometry of the laser. Hence, field-intensity profiles of four transverse leaky modes (i.e., LM_{01}^c, LM_{01}^s, LM_{11}^c, and LM_{11}^s), carrier concentration, and heat are calculated self-consistently [5]. In addition, the influence of SHB and thermal lensing effects (including carrier- and heat-induced index change) are carefully taken into consideration along the transverse and azimuthal directions. If the influence of birefringence is taken into consideration, the leaky modes LM_{01}^c and LM_{11}^c (LM_{01}^s and LM_{11}^s) will experience a small change in refractive index $\Delta n_c(\Delta n_s)$ inside the core region of the ARROW. A complete description of the model together with the detail of parameters can be found in [5].

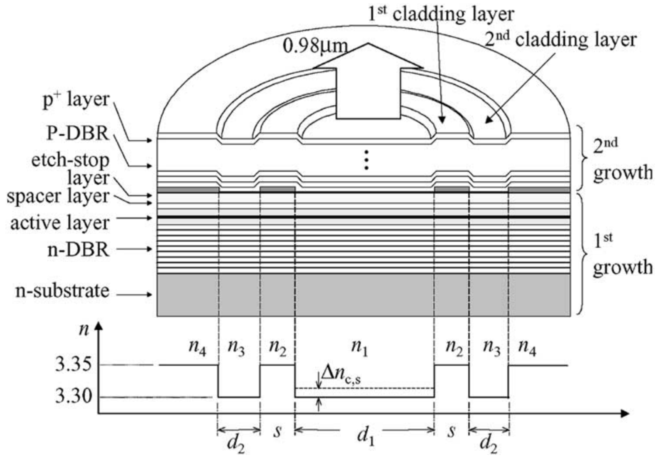

Fig. 1. Schematic of the birefringent ARROW VCSELs used in the analysis.

The influence of birefringence on the excitation of multitransverse leaky modes in a 12-μm core diameter ARROW VCSEL is studied. It is assumed that the thickness of the cladding layers s and d_2 are set to 1.3 and 6 μm, respectively. These values of s and d_2 are selected under the planar approximation method for the minimum radiation loss of the fundamental transverse leaky mode [6]. Fig. 2 shows the light–current curves and net optical

---

Manuscript received Septemper 2, 2003; revised October 28, 2003.

The authors are with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore (e-mail: esfyu@ntu.edu.sg).

Digital Object Identifier 10.1109/LPT.2004.823748

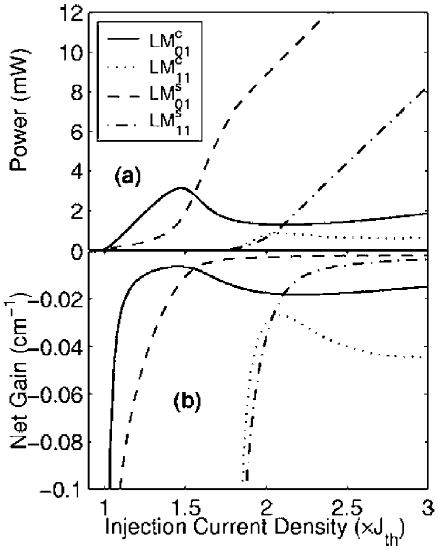

Fig. 2. (a) Light–current curves and (b) net gain versus normalized injection current for the birefringent ARROW VCSELs with $s = 1.3$ μm, $d_2 = 6$ μm, $\Delta n_c = 2 \times 10^{-4}$, and $\Delta n_s = 0$ for the four transverse leaky modes.

gain versus injection current of the birefringent ARROW VCSELs. In the calculation, it is assumed that $\Delta n_c = 2 \times 10^{-4}$ and $\Delta n_s = 0$ so that the resonant frequency of LM_{01}^c (LM_{11}^c) is slightly higher than that of LM_{01}^s (LM_{11}^s). The existence of Δn_c is due to strain-induced birefringence and its value is estimated from the wavelength difference (i.e., ~ 0.5 Å) betweem the two polarizations obtained experimentally [2]. It is observed that polarization switching between LM_{01}^c and LM_{01}^s occurs at injection level equal to $\sim 1.55\times$threshold. The increase in (reduction of) modal gain (radiation loss), which is a function of the index profile, causes the polarization switching. It can be shown that the heat-induced index change can be $> 1 \times 10^{-2}$, which is $\sim$5 times greater than that can be obtained from the carrier-induced index change [5]. Hence, it is believed that thermal lensing effects are the dominant mechanism of polarization switching. Furthermore, the excitation and polarization switching of LM_{11}^c and LM_{11}^s, which are also dominated by thermal lensing effects, occur at injection level $\geq 2.1 \times$ threshold.

Poor suppression of polarization switching in the birefringent ARROW VCSELs is mainly due to the small radiation loss difference between the LM_{01}^c and LM_{01}^s. Hence, a new design rule, which 1) maximizes the radiation loss difference between LM_{01}^c and LM_{01}^s and 2) maintains a low radiation loss in LM_{01}^c, is proposed to optimize the ARROW structure for the suppression of polarization switching. The design rule can be implemented by the following steps: 1) Initially, the influence of birefringence is ignored (i.e., $\Delta n_c = \Delta n_s = 0$) in the design based on cold cavity analysis. For a given value of d_1, the values of s and d_2 are optimized to minimize the radiation loss of LM_{01}. 2) Then, with the inclusion of birefringence into the cold cavity analysis (i.e., $\Delta n_c = 2 \times 10^{-4}$ and $\Delta n_s = 0$), the value of s is allowed to increase in order to increase the radiation loss difference between LM_{01}^c and LM_{01}^s. However, the variation of s is restricted to 1) the radiation loss of LM_{01}^c is not excessively higher than its minimum value, and 2) the radiation loss of LM_{11} (also other high-order transverse leaky modes) should be higher than that of LM_{01}. The value of d_2 is kept unchanged because the radiation loss difference is less dependent on d_2.

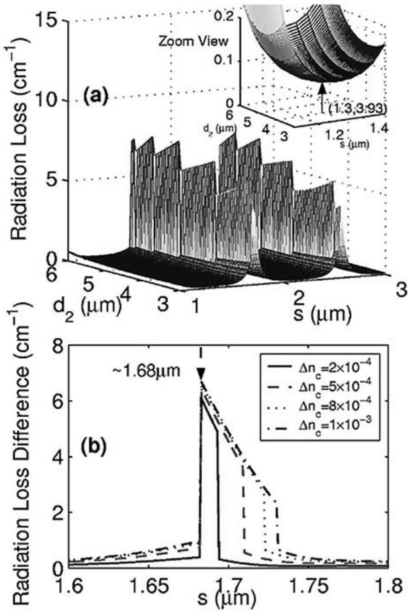

Fig. 3. (a) Plots of radiation loss of LM_{01} versus s and d_2. The inserted diagram is the enlargement of radiation loss of LM_{01} in range of 1 μm $< s <$ 1.5 μm and 2 μm $< d_2 <$ 6 μm. (b) Radiation loss difference between LM_{01}^c and LM_{01}^s for Δn_c varies between 2×10^{-4} and 10×10^{-4}.

The new design rule is applied to design a 12-μm core diameter birefringent ARROW VCSEL: 1) The values of s and d_2 are calculated for minimum radiation loss of LM_{01} (for the case where $\Delta n_c = \Delta n_s = 0$). Fig. 3(a) plots the radiation loss of LM_{01} versus s (i.e., 1 μm $< s <$ 3 μm) and d_2 (i.e., 3 μm $< d_2 <$ 6 μm) by cold-cavity simulation [3]. If $s <$ 2 μm is required in the design of ARROW, it can be shown that the optimum values of s and d_2 are found to be 1.3 and 3.93 μm, respectively, with the corresponding radiation loss equal to $\sim$0.08 cm^{-1}. 2) Birefringence is now taken into consideration and the value of s is allowed to increase for a larger radiation loss difference between LM_{01}^c and LM_{01}^s. Fig. 3(b) shows the radiation loss difference between LM_{01}^c and LM_{01}^s versus s. It is observed that if s increases from 1.3 to 1.68 μm, the corresponding radiation loss difference increases from $\sim$ 0.02 cm^{-1} to $\sim$ 6 cm^{-1}. The solid, dashed, dotted, and dashed–dotted lines in the figure represent $\Delta n_c = 2 \times 10^{-4}, 5 \times 10^{-4}, 8 \times 10^{-4}$, and 10×10^{-4}, respectively, but the other parameters remain unchanged. This indicated that the variation of Δn_c will not deteriorate the radiation loss difference between LM_{01}^c and LM_{01}^s at $s =\sim 1.68$ μm, and the suppression of polarization switching is, therefore, robust to the uncertainty of Δn_c. Radiation losses of all transverse leaky modes are also calculated for $s = 1.68$ μm and $d_2 = 3.93$ μm. It can be shown that LM_{01}^c has the lowest radiation loss and the mode with the second lowest loss is LM_{01}^s, followed by LM_{11}^c and LM_{11}^s. Other high-order transverse leaky modes have much higher radiation losses so can be ignored in the analysis. Fig. 4 shows the steady-state characteristics of the ARROW VCSELs with dimensions obtained by the new design rule (i.e., $s = 1.68$ μm, $d_2 = 3.93$ μm). From the light–current curves, it is found that the maximum power of LM_{01}^c increases from $\sim$3 to $\sim$10.8 mW (i.e., improved by more than

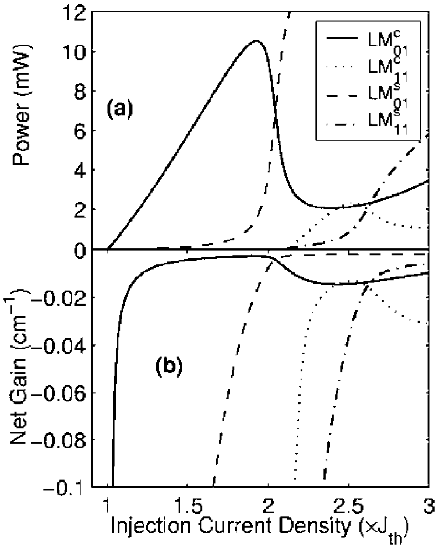

Fig. 4. (a) Light–current curves and (b) net gain versus normalized injection current for the new designed birefringent ARROW VCSELs with $s = 1.68\ \mu$m, $d_2 = 3.93\ \mu$m, $\Delta n_c = 2 \times 10^{-4}$, and $\Delta n_s = 0$ for the four transverse leaky modes.

three times). In addition, the required injection current to switch from LM_{01}^c to LM_{01}^s increases from 1.57 × threshold to 2.1 × threshold. It can also be shown that the threshold current for the optimized structure is only slightly increased by less than 10%. Hence, it is possible to suppress polarization switching in VCSELs using optimized ARROW structure.

III. DISCUSSION AND CONCLUSION

The above-threshold characteristics of birefringent ARROW VCSELs are studied. It can be shown that polarization switching and excitation of high-order transverse leaky modes are mainly affected by thermal lensing effects. A new design rule is also proposed to optimize the dimensions of ARROW VCSELs for better suppression of polarization switching. Hence, it can be shown that the maximum single-polarization output power can be improved by more than three times. Furthermore, the performance of the optimized ARROW VCSELs will not be deteriorated by the uncertainty of birefringence.

REFERENCES

[1] M. P. van Exter, A. K. J. van Doorn, and J. P. Woerdman, "Electro-optic effect and birefringence in semiconductor vertical cavity lasers," *Phys. Rev. A*, vol. 56, no. 1, pp. 845–853, 1997.
[2] Y. Hong, K. A. Shore, A. Larsson, M. Ghisoni, and J. Halonen, "Polarization switching in a vertical cavity surface emitting semiconductor laser by frequency detuning," *Inst. Elect. Eng., Optoelectronics*, vol. 148, no. 1, pp. 31–34, 2001.
[3] 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.
[4] 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.
[5] S. F. Yu, "Polarization selection in birefringent antiresonant reflecting optical waveguide-type vertical cavity surface emitting lasers," *IEEE J. Quantum Electron.*, vol. 39, pp. 1362–1371, Nov. 2003.
[6] 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.