

# Novel polarization controller based on injection-locked vertical-cavity surface-emitting laser

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**Abstract:** A novel polarization controller using the transverse mode switching of a vertical-cavity surface-emitting laser (VCSEL) induced by injection locking is proposed. The operating principle is based on an all-optical inverter using transverse mode switching of an elliptical-shaped VCSEL keeping a stable polarization state. We carried out the modeling based on a multi-transverse-mode rate equation analysis, exhibiting the potential of high-speed polarization control at 5 Gbps.

**Keywords:** injection locking, polarization control, vertical-cavity surface-emitting laser (VCSEL)

**Classification:** Photonics devices, circuits, and systems

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## 1 Introduction

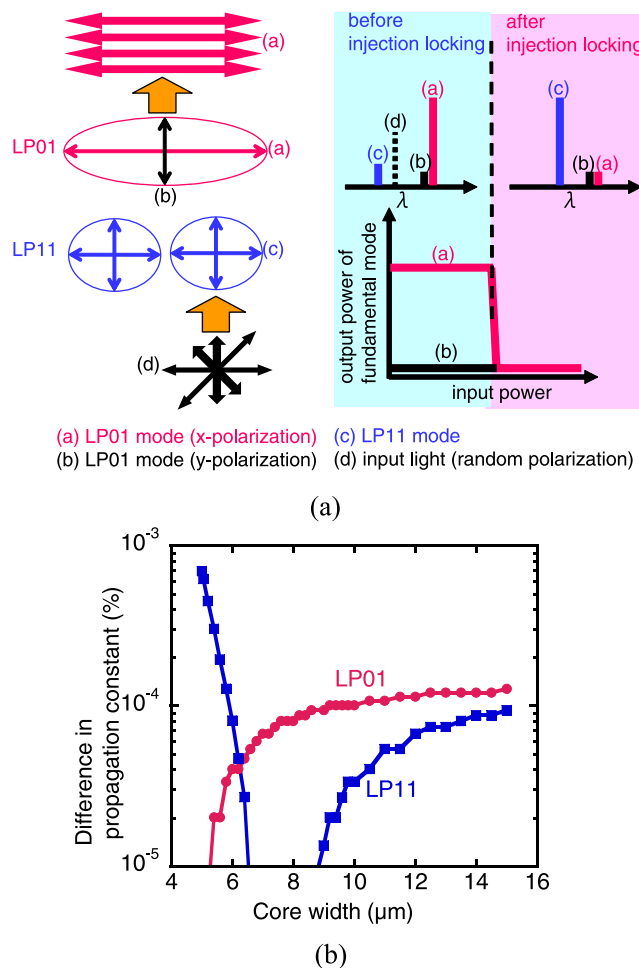
Vertical cavity surface emitting lasers [1] have been attracting much interest with various unique features such as small footprint, low power consumption and polarization insensitivity for use in future photonic networks. Novel applications of VCSELs for all-optical signal processing have been also discussed and several studies have been made, which include an optical inverter, a limiter, a 2R/3R regenerator, a buffer memory and so on [2, 3, 4, 5]. We have proposed and demonstrated an optical signal processing device based on the transverse mode switching of a two-mode VCSEL with injection locking [3, 4, 5]. The polarization control of randomly polarized signal light in single-mode fibers is one of remaining issues for future photonic networks involving polarization-dependent optical devices. In this paper, we propose a novel polarization controller using an injection-locked VCSEL. The proposed device is based on the operating principle of an optical inverter we previously demonstrated [5]. The elliptical-shaped cavity enables us to obtain the stable polarization state for a fundamental transverse mode, while two orthogonal polarization states of the high-order transverse mode are degenerated. We present a rate equation analysis for both static and dynamic operations of the proposed device. The result shows a possibility of realizing a high speed polarization controller using a VCSEL, which would be useful for signal coherent detection and the elimination of the polarization dependence of optical devices used in photonic networks.

## 2 Principles and calculation model

Figure 1 (a) illustrates the operating principle of the proposed polarization controller using a VCSEL-based optical inverter with an elliptical active region. When external light is injected to the high-order mode of a VCSEL with the wavelength slightly longer than that of a free-running VCSEL, the dominant lasing mode is abruptly switched from the fundamental mode to the high-order mode at some threshold input power due to injection locking [5]. Thus, the output of the fundamental mode shows an inverter behaviour as a function of the input light of the high-order mode. The numerical simulation shows that two orthogonal polarization states of LP11 high order modes are degenerated while the polarization state of a LP01 fundamental transverse mode can be stably fixed for a properly designed elliptical-shaped VCSEL. When we inject signal light into the high-order mode, the switching characteristics of the LP11 high-order modes can be polarization-insensitive. On

the other hand, the polarization state of the fundamental mode can be stably controlled with a help of an elliptical active region shape. Thus, the input signal of randomly polarized light can be converted to the output of the fundamental mode with a fixed linear polarization state. The polarization state of the output can be fixed for any polarization states of input light. The modulation waveform can be transferred to the output of the fundamental mode with signal inversion.

Figure 1 (b) shows the calculated difference in the propagation constant between two orthogonal polarization states for transverse modes of an elliptical-shaped VCSEL. The calculation was carried out for a LP01 fundamental mode and LP11 high-order mode by using the full-vectorial simulator of FIMMWAVE/FIMMPROP (Photon Design Co.). In this analysis, we assumed that the structure of a VCSEL for lateral confinement is expressed by a rectangular core whose one side length is  $5\text{ }\mu\text{m}$ . Figure 1 (b) shows the birefringence of the rectangular core as a function of the width of other side. The result shows that a proper choice of asymmetry provides both the degeneracy of LP11 polarization modes and the non-degeneracy of LP01 po-



**Fig. 1.** (a) Principle of a polarization controller using all-optical inverter and active elliptical aperture. (b) Difference in propagation constant as changing the core width.

larization modes. This would be important for our polarization controller as explained previously.

We carried out the numerical simulation by using the following rate equations.

$$\frac{dN}{dt} = \frac{I\eta_i}{eV_a} - \frac{N}{\tau_s(N)} - v_g \sum_p G_p(N, S_p) S_p, \quad (1)$$

$$\frac{dS_q}{dt} = \left( \Gamma v_g G_q(N, S_p) - \frac{1}{\tau_q} \right) S_q + \beta B N^2 \quad (2)$$

$$\frac{dS_r}{dt} = \left( \Gamma v_g G_r(N, S_p) - \frac{1}{\tau_r} \right) S_r + 2\kappa \sqrt{S_r S_{in}} \cos(\Delta\omega t - \phi_r) + \beta B N^2 \quad (3)$$

$$\frac{d\phi_r}{dt} = \frac{\alpha}{2} \left( \Gamma v_g G_r(N, S_p) - \frac{1}{\tau_r} \right) S_r + \kappa \sqrt{\frac{S_{in}}{S_r}} \sin(\Delta\omega t - \phi_r) \quad (4)$$

$$(p = fx, fy, hx, hy), (q = fx, fy), (r = hx, hy)$$

where the subscript  $f$  and  $h$  denote a fundamental mode and first-high-order mode, respectively. Additionally, the subscript  $x$  and  $y$  denote the polarization directions.  $N$  the carrier density,  $S$  the photon density,  $\phi_r$  the phase of the electric field,  $S_{in}$  the injected photon density and  $\Delta\omega = \omega_{in} - \omega_h$  the frequency detuning of the injected signal from the frequency  $\omega_h$  of the first-high-order mode of the free-running VCSEL. The effect of the spatial hole burning and the spectral hole burning are included in these equations as the gain saturation term  $G(N, S_p)$ . The parameters used in the calculation are referred from references for 1.55  $\mu\text{m}$  InP-based lasers [6, 7, 8]. We used multi mode rate equations which include orthogonally polarization states and the external optical injection term is added either orthogonally polarization states of first-high-order mode rate equation. The effect of an elliptical aperture is assumed by providing the loss difference between two orthogonally polarization states of each mode, fundamental mode and first-high-order mode. An ideal condition for our polarization controller is that two orthogonally polarization states are completely degenerate in first-high-order modes, which is the case with a zero- loss difference for two polarization states. Figure 2 shows the calculation model. When the external light with linear polarization is injected into the two orthogonally polarization states of the first-high-order mode with some amount of loss difference, we calculate the output of two orthogonally polarization states of the fundamental mode.

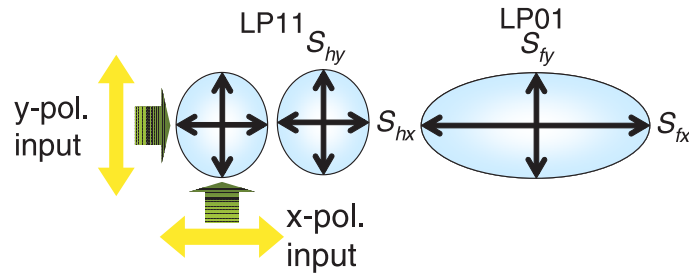
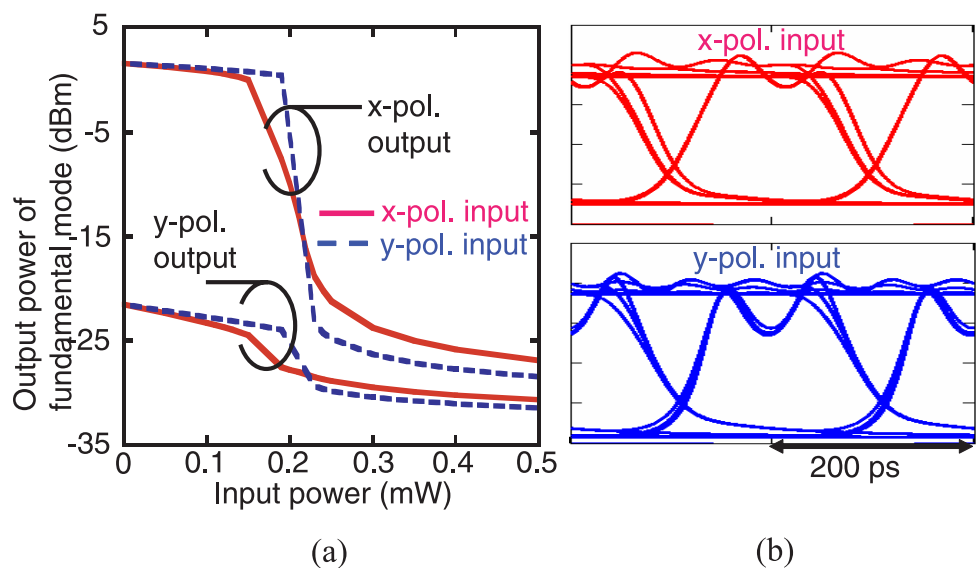


Fig. 2. Calculation model.

### 3 Result

We carried out the numerical simulation for our proposed device using rate equations including two transverse modes with two orthogonal polarization states. Figure 3(a) shows the result of the optical input-output characteristics. We assumed input light with two orthogonal polarization states for LP11 high-order modes. Solid lines are the result with the x-polarization input and dashed lines are that with y-polarization input. We assumed that the loss difference between two orthogonal polarization modes are 3% and 10% for LP11 high-order modes and for LP01 fundamental mode, respectively. Because the polarization state of the fundamental mode is stably fixed with help of the large difference in the two orthogonal polarization state, its polarization suppression ratio is over 20 dB. Also, the fundamental mode can oscillate with a fixed polarization even for the injection of two orthogonal polarization input light. The extinction ratio of x-polarization output is over 30 dB. The detuning between the wavelength of the input light and that of the first-high-order mode of the free-running VCSEL ( $\Delta\lambda = \lambda_{in} - \lambda_{LP11}$ ) was set to be 0.15 nm, which is an important parameter to obtain the abrupt switching without hysteresis loop in the static switching characteristic. Figure 3(b) shows calculated eye patterns of the x-polarization output of the fundamental mode for the input signal of 5 Gbps NRZ-PRBS. We can see clear eye opening. From the both static and dynamic characteristics, the operation of the polarization controller can be demonstrated for randomly polarized input light, while some loss difference (3%) between the two orthogonal polarization modes of the LP11 high-order mode can be accepted.

However, the increase in the loss difference produces polarization sensitivity, yielding change in extinction ratio and threshold switching power. To avoid this polarization sensitivity, an appropriate design of the aperture of the



**Fig. 3.** Calculated (a) Optical input-output characteristics and (b) eye patterns of output of the fundamental mode.

VCSEL is required. Some more detailed analysis will be reported elsewhere. The operating speed of the present polarization controller is limited by the optical modulation bandwidth and the relaxation oscillation frequency of the VCSEL. We expect high speed direct modulation over 10 Gbps for long wavelength VCSELs. High speed VCSELs and the addition of assist light would be helpful for increasing the speed of the proposed polarization controller to go beyond 10 Gbps.

#### 4 Summary

We proposed a novel polarization controller based on injection locked VCSELs. The operating principle is based on an all-optical inverter using transverse mode switching. Multi-mode rate equation analysis was carried out and high-speed polarization control is predicted for input signal of 5 Gbps with two orthogonal polarization states. A novel concept based on an injection-locked VCSEL may enable high-speed polarization control.

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