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All-optical regenerator with re-polarization function based on dual optical injection VCSEL

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Abstract: We propose a novel optical-regenerator based on two-transverse mode VCSEL with dual optical-injection locking. The non-linear transfer function in input-output characteristics enables us to reshape the degraded input signal. In addition, the polarization state of the output signal can be tightly controlled. The CW assist light injected into the fundamental transverse mode increases the speed and stabilizes the polarization of the output light at the same time. A possibility of 4R (3R+Re-polarization) regeneration at 10 Gbps is suggested.

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

Classification: Photonics devices, circuits, and systems

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ELectronics EXpress

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1 Introduction

All-optical regeneration would be one of key issues for future all-optical networks. Vertical cavity surface emitting lasers have been attracting much interest with various unique features such as small footprint and low power consumption [1]. Some device applications of VCSELs have been studied for use in all-optical signal processing, which include an optical inverter, a limiter, a 2R/3R regenerator, a buffer memory, polarization controller and so on [2, 3, 4, 5, 6]. We have proposed and demonstrated an optical regenerator based on the transverse mode switching of a two-mode VCSEL with injection locking. We presented some results on optical regeneration experiments using an InP-based VCSEL inverter [5]. The nonlinear transfer function in input-output characteristics enables us to reshape the degraded input signal at 1 Gbps. We also proposed and modeled a polarization controller using the inverter, which gives us polarization control behavior at 5 Gbps for randomly polarized input signals [6]. However, the operating speed is limited by the relaxation oscillation frequency and modulation bandwidth of VCSELs. It is noted that fast direct modulation beyond 40 GHz in VCSELs was demonstrated using an injection locking scheme [7]. In this paper, we propose a novel optical-regenerator based on two-transverse mode VCSEL with dual optical-injection locking. The CW assist light injected into the fundamental mode increases the speed of the regenerator and stabilizes the polarization state of the output light at the same time. We present the rate equation analysis of two-mode injection-locking for both the fundamental mode and high-order mode. The result shows that the CW optical injection yields the optical reshaping as well as high speed polarization control for randomly polarized incident light at 10 Gbps. A high orthogonal polarization suppression ratio (OPSR) of 20 dB and an extinction ratio of 10 dB are predicted. With adding an electrical clock signal, reshaping and retiming function can be obtained. The novel 4R (3R+Re-polarization) regenerator would be useful in future photonic networks involving polarization-dependent optical devices.

2 Proposed Scheme

The principle of the proposed optical regeneration, which is based on a VCSEL-based optical inverter [4], is shown in Fig. 1. Signal light with a wavelength slightly longer than that of a LP02 high-order transverse mode is injected into a free-running VCSEL operating in a LP01 fundamental transverse mode. When the high-order mode is injection-locked by the signal light, the dominant lasing mode switches from the fundamental mode to the

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high-order mode, resulting in the abrupt reduction in the output power of the fundamental mode. By extracting the output power of the fundamental mode as an output signal, a regenerated output signal can be obtained with a step-like transfer function. CW assist light with a fixed polarization is injected into the LP01 fundamental mode. The injection-locking into the fundamental mode increases the relaxation oscillation frequency of the VCSEL [7], resulting in the increased speed of the regenerator. Also, we can obtain the stable polarization control of the fundamental mode, since the polarization state of the fundamental mode is fixed with the polarization of the CW assist light. According to our experimental result, we found that the LP02 high-order mode for the input signal injection is suitable for polarization-insensitive operation of the optical regenerator. This device gives us a non-linear transfer function as well as stable polarization of output signal at the same time even for randomly polarized input light.

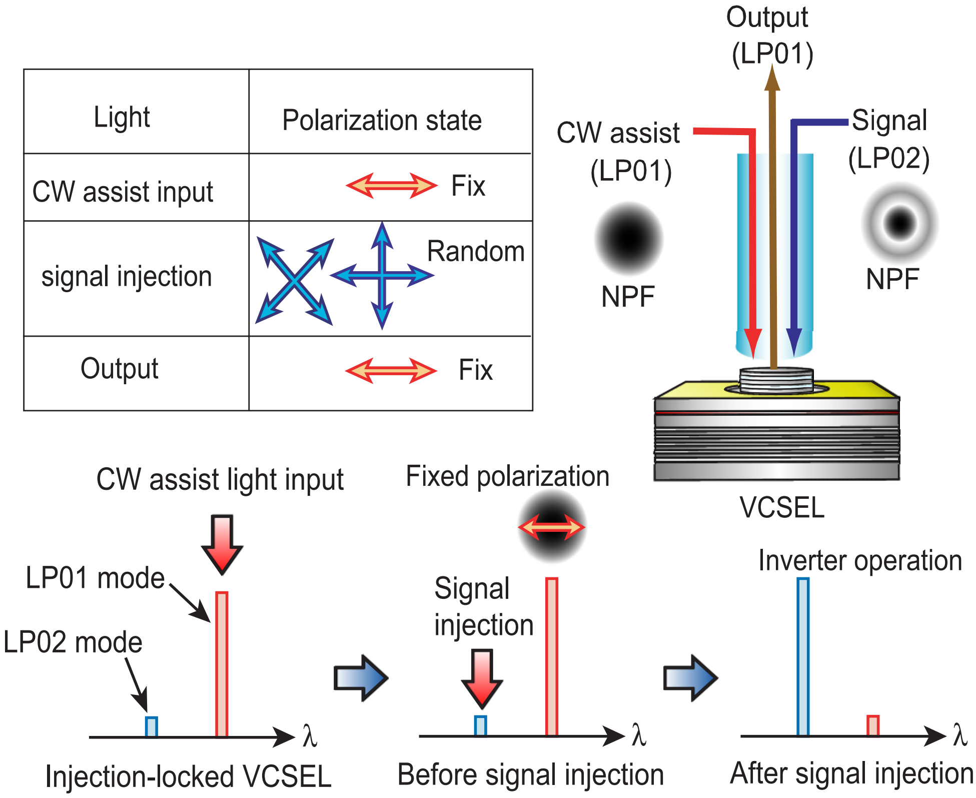

Fig. 1. Dual injection-locked VCSEL for all-optical regeneration with stable polarization output.

3 Modeling Results

We carried out the numerical simulation based on the following rate equation analysis. All device parameters used in this calculation are the same as those in our previous work [6].

$$\frac{dN}{dt} = \frac{I\eta_i}{eV_a} - \frac{N}{\tau_s(N)} - v_g \sum_p G_p(N, S_p)S_p, \quad (p = fx, fy, hx, hy) \qquad (1)$$

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$$\frac{dS_{fx}}{dt} = \left(\Gamma v_g G_{fx}(N,S_p) - \frac{1}{\tau_{fx}}\right) S_{fx} + 2\kappa\sqrt{S_{fx}S_a}\cos(\Delta\omega_a\, t - \phi_f) + \beta B N^2 \quad (2)$$

$$\frac{d\phi_f}{dt} = \frac{\alpha}{2}\left(\Gamma v_g G_{fx}(N,S_p) - \frac{1}{\tau_{fx}}\right) S_{fx} + \kappa\sqrt{\frac{S_a}{S_{fx}}}\sin(\Delta\omega_a\, t - \phi_f) \quad (3)$$

$$\frac{dS_{fy}}{dt} = \left(\Gamma v_g G_{fy}(N,S_p) - \frac{1}{\tau_{fy}}\right) S_{fy} + \beta B N^2 \quad (4)$$

$$\frac{dS_{hx}}{dt} = \left(\Gamma v_g G_{hx}(N,S_p) - \frac{1}{\tau_{hx}}\right) S_{hx} + 2\kappa\sqrt{S_{hx}S_{in}}\cos(\Delta\omega\, t - \phi_h) + \beta B N^2 \quad (5)$$

$$\frac{d\phi_h}{dt} = \frac{\alpha}{2}\left(\Gamma v_g G_{hx}(N,S_p) - \frac{1}{\tau_{hx}}\right) S_{hx} + \kappa\sqrt{\frac{S_{in}}{S_{hx}}}\sin(\Delta\omega\, t - \phi_h) \quad (6)$$

$$\frac{dS_{hy}}{dt} = \left(\Gamma v_g G_{hy}(N,S_p) - \frac{1}{\tau_{hy}}\right) S_{hy} + \beta B N^2 \quad (7)$$

where the subscript f and h denote a fundamental mode and high-order mode, respectively. Also, the subscript x and y denote the polarization directions. N the carrier density, S the photon density, ϕ the phase of the electric field, S_{in} and S_a the injected photon density and $\Delta\omega = \omega_{in} - \omega_h$ and $\Delta\omega = \omega_{in} - \omega_f$ the frequency detuning of the injected signal from the frequency of the high-order mode and the fundamental mode of the free-running VCSEL, respectively. The effects of the spatial hole burning and the spectral hole burning are included in these equations as the gain saturation term $G(N, Sp)$. In case of circular aperture VCSELs, two orthogonally polarization states of LP01 and LP02 mode are degenerated for the circularly symmetric VCSEL. The CW assist light with a fixed polarization is injected into the LP01 mode to increase the speed of the VCSEL and to realize the stable polarization of the output (LP01 mode). The signal light with randomly polarization is injected into the LP02 mode. We calculated both the static and dynamic characteristics of the proposed device. Figure 2 (a) shows the calculated optical input-output characteristic and orthogonal polarization suppression ratio (OPSR) of the LP01 mode with wavelength detuning for optical injection. The wavelength detuning for the signal light and the assist light is assumed to be 0.32 nm and 0.11 nm, respectively. Detailed optimization for wavelength detuning will be discussed elsewhere. We expect a high OPSR of 20 dB and nonlinear inverter behavior with a 10 dB extinction ratio. We also investigated the dynamic behavior of the proposed device at 10 Gbps with NRZ format. The calculated eye patterns of the output inverted signal for the polarization states parallel and orthogonal to the assist light polarization are shown in Figs. 2 (b) and 2 (c), respectively. The polarization of the LP01 mode output can be fixed with the polarization of the assist light. The wavelength detuning parameters are same as those of the static characteristics in Fig. 2 (a). The eye opening of the parallel polarization is clearly seen with a 10 dB extinction ratio and the orthogonal polarization could be suppressed with 20 dB OPSR. It is noted that the polarization insensitive

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operation can be expected for any polarization states of input signal, since the LP02 mode is circularly symmetric.

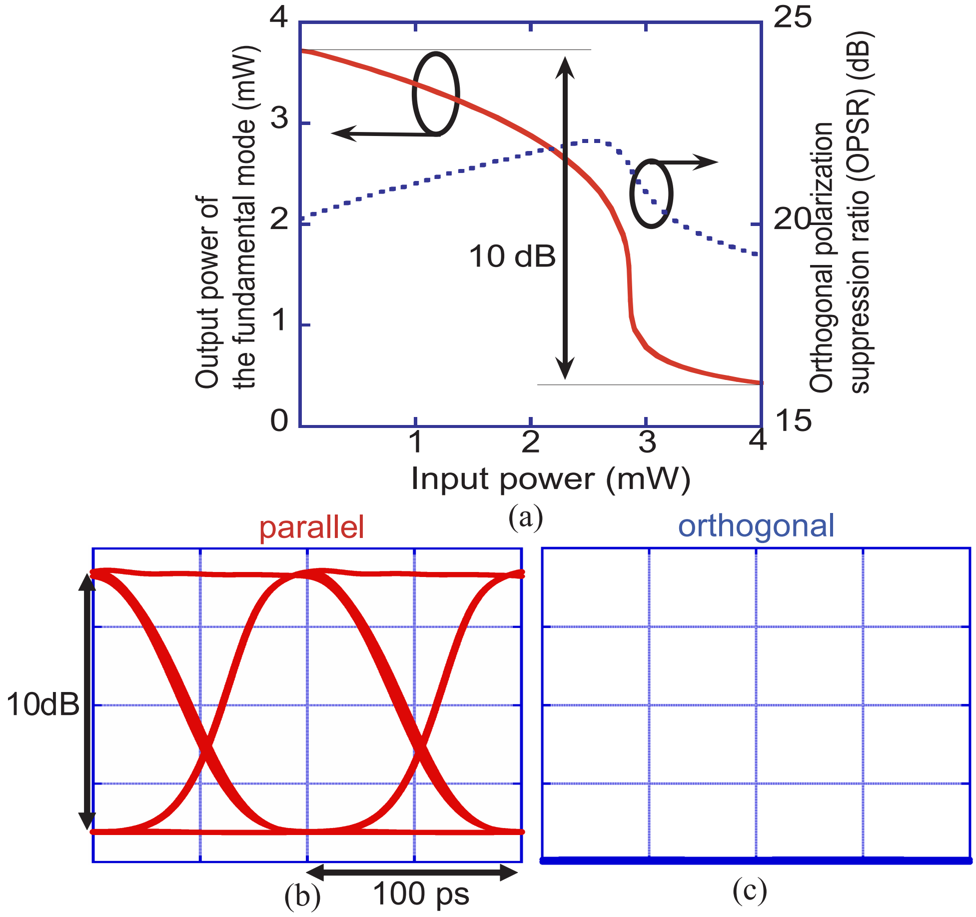

Fig. 2. (a) Calculated optical input-output characteristic and OPSR, and calculated eye patterns of inverted output signal for (b) parallel and (c) orthogonal polarization states of the LP01 mode.

4 Optical Regeneration

The injection-locked VCSEL can be electrically driven by the clock signal, which generates short pulses of the fundamental mode. The output power of the fundamental mode is suppressed when the distorted signal is injected into the high-order mode. In absence of the input signal, the VCSEL operates in the fundamental mode. The VCSEL is injection-locked by the 0.2 mW CW assist light injected to the fundamental mode. After reaching the steady state, the injection-locked VCSEL starts to be driven by a 10 GHz electrical clock signal. The modulation current amplitude is assumed to be 6 mA. The 10 Gbps RZ input signal shown in Fig. 3 (a) is injected into the LP02 high-order mode of the injection-locked VCSEL. The input peak power is ~1.5 mW and the wavelength of the input signal is set to be 0.35 nm longer than that of the high-order mode. Figure 3 (b) shows the calculated eye di-

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agrams for the output signal of the LP01 fundamental mode. The distorted input signal is regenerated to the polarity-inverted signal. Amplitude fluctuations and timing jitters calculated for 10 Gbps RZ signals can be reduced. When the output power of the fundamental mode is filtered out, 3R regeneration can be realized with a stable polarization state along with a CW assist light. Thus, the regenerated signal with a fixed polarization can be obtained by the proposed regenerator for the distorted input signal with random polarization. This scheme would enable novel 4R (3R+Re-porarization) regeneration.

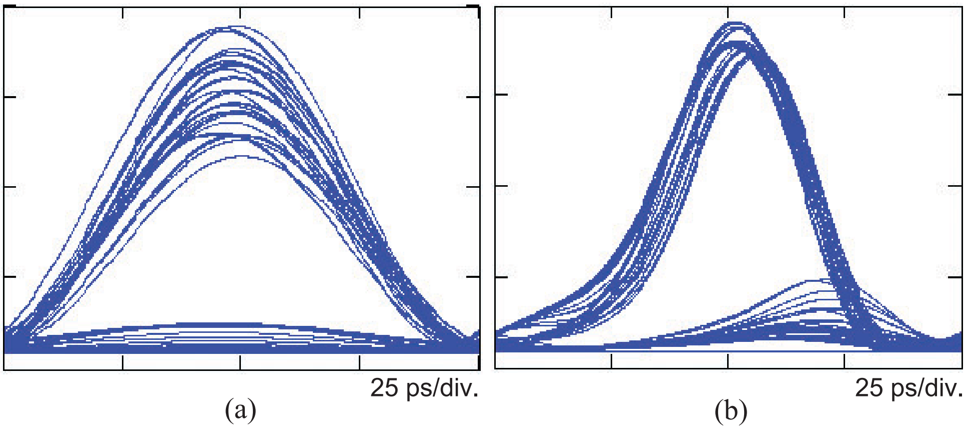

Fig. 3. Eye diagram for (a) a distorted input signal and (b) a regenerated signal at 10 Gbps.

5 Conclusions

We proposed a novel all-optical regenerator based on a dual optical injection-locked VCSEL. The CW assist light injected into the fundamental mode increases the speed of the regenerator and stabilizes the polarization state of the output light at the same time. It was numerically shown that all-optical 3R regeneration can be realized for 10 Gbps operations. The proposed 3R regenerator enables a novel additional function of re-polarization for randomly polarized input, which would be so-called 4R regeneration.

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