Low power penalty tunable slow light using vertical-cavity surface-emitting laser amplifier

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Received November 11, 2010; accepted December 6, 2010; posted online April 18, 2011

A tunable slow light of 2.5-Gb/s pseudo-random binary sequence signal using a 1550-nm vertical-cavity surface-emitting laser (VCSEL) is experimentally demonstrated. The influences of the bias current and the gain saturation on the slow light are investigated. With bias current increasing, tunable optical group delay up to 98 ps is obtained at room temperature. Demonstration of the time delay between 16 and 24 ps by signal intensity change is reported. Under an appropriate bias current, by tuning the input signal to track the peak gain wavelength of the VCSEL, slow light of a power penalty as low as 1 dB is achieved. With such a low power penalty, the VCSEL has a great potential application as a compact optical buffer.

OCIS codes: 140.7260, 210.4680, 190.5970.

doi: 10.3788/COL201109.051401.

Recently, there has been a great deal of interest in slowing light for significant applications in optical communication, optical buffer, signal processing, and phase-array antenna systems[1−8]. In particular, tunable slow light using the vertical-cavity surface-emitting laser (VCSEL) is very attractive because the VCSEL has the advantages of low power consumption, narrow beam divergence, and low cost production[9]. For VCSELs, optical group delay can be obtained by introducing a larger positive dispersion of the phase caused by a change in the gain spectra via coherent population oscillation effect[9−12]. Over the last couple of years, most of the slowlight experiments in VCSELs have been demonstrated with sinusoidal modulation signals[9−12]. These experimental results suggest that time delays are dependent on the frequency of modulation[9]. In practice, these delay differences have no influence on the signal distortion of sinusoidal modulation due to their narrow bandwidth. However, different from sinusoidal signal, the pseudo-random binary sequence (PRBS) signal, as required in most communication applications, is composed of a series of frequency components, so that the flat gain and time delay of VCSELs over all the signal bandwidths are required to avoid signal distortion. Thus, to obtain the maximum achievable fractional delay without distortion, the studying the slow light characteristics of VCSELs with broadband modulation signals in detail for a practical application is necessary.

In this letter, tunable delay of PRBS signal using a 1550-nm quantum well (QW) VCSEL operated as a Fabry-Perot (FP) amplifier[13] is experimentally demonstrated. The dependencies of group delays on the gain saturation of the VCSEL are also investigated in our experiments. By carefully adjusting the wavelength of the signal light to coincide with the peak gain wavelength of the VCSEL, tunable slow light of a power penalty as low as 1 dB is achieved.

The slow light experimental setup is illustrated in Fig. 1. The slow light device used in the experiment was a monolithically single-mode 1550-nm QW VCSEL (RayCan RC32xxx1-F, RayCan, Korea) operated in reflection mode. Light from a tunable laser was modulated by 2.5 Gb/s PRBS signal through a Mach-Zehnder modulator. After passing through a polarization controller and an optical attenuator, the PRBS signal was divided into two parts by a coupler: one was injected into the VCSEL through an optical circulator and the other was monitored by an optical power meter. The reflected output of the VCSEL was then amplified, and an optical filter was used to remove the amplified spontaneous emission (ASE) noises. Finally, group delay was detected by an oscilloscope. To synchronize the oscilloscope and set a reference for the group delay, half of the modulation signal was fed into the trigger input. To analyze the quality of the slow light, a bit error rate tester (BERT) is also used to measure the bit error rate (BER).

To select the appropriate bias currents of the VCSEL and the signal wavelength, the optical spectrum and light-current characteristic of the VCSEL are measured firstly and are given in Fig. 2. The threshold $I_{\rm th}$ of the VCSEL is about 2 mA, and the peak wavelength of the optical spectrum is about 1531.92 nm. Although the current is biased from 1.6 to 2.05 mA in our slow light experiment, the VCSEL works within a FP amplifier regime. The tunable laser wavelength is fine tuned to track the peak gain wavelength of the VCSEL when the bias

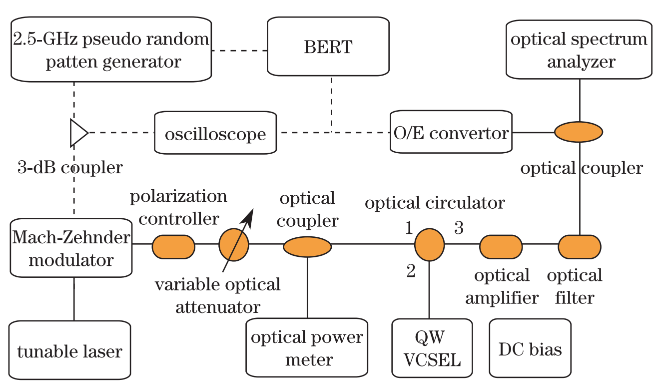

Fig. 1. Experimental setup. O/E: optical-to-electrical; DC: direct current.

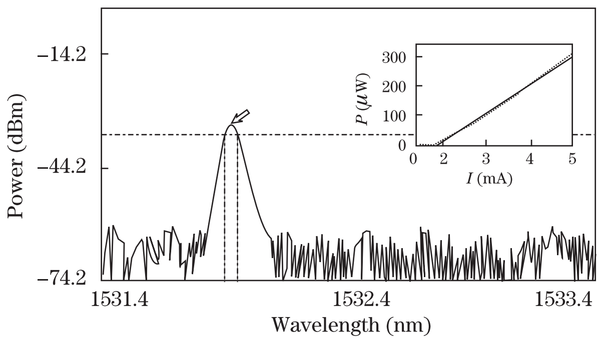

Fig. 2. Optical spectra of the VCSEL biased at the current I of 2.0 mA. The inset is the light-current characteristic of the QW VCSEL.

current is changed. For the bias current still below the threshold, a profile of the reflection spectrum is observed exhibiting a 3-dB bandwidth of 7 GHz. For this bandwidth limitation, time domain measurements are performed by imposing a 2.5-Gb/s PRBS signal onto the laser.

The delayed modulation traces and corresponding eye diagrams of 2.5-Gb/s PRBS signals at various bias currents are presented in Figs. 3 and 4, respectively. The time-domain reference trace is taken when the VCSEL is turned off, and then the time delay is defined using the metrics of the maximum eye-opening penalty[14]. In Fig. 3, with the bias current tuned to the threshold, the increased delay of the PRBS signal is observed. This phenomenon is caused by the enlarged gain. When the VCSEL is operated in the amplifier mode, the increased bias current contributes to the enhanced gain. This gain enhancement ties to a larger positive dispersion of the phase. Thus, an increase in the delay is expected and demonstrated in this experiment.

The time-domain traces and eye diagrams indicate that good signal quality can be achieved when the bias current of the VCSEL is low to have enough gain and time delay

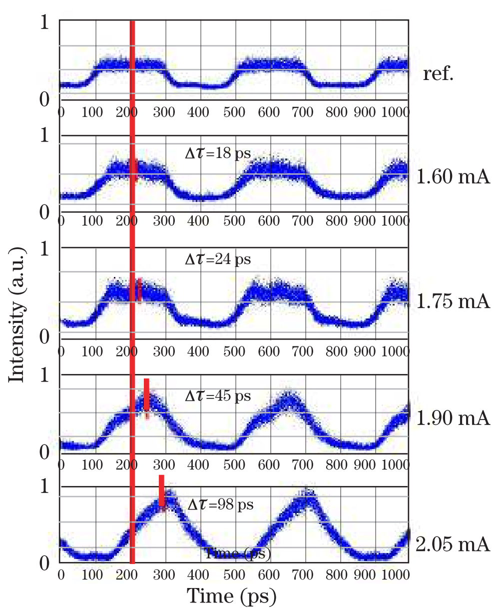

Fig. 3. Measured delays for the 2.5-Gb/s PRBS under different bias conditions with –27-dBm input power.

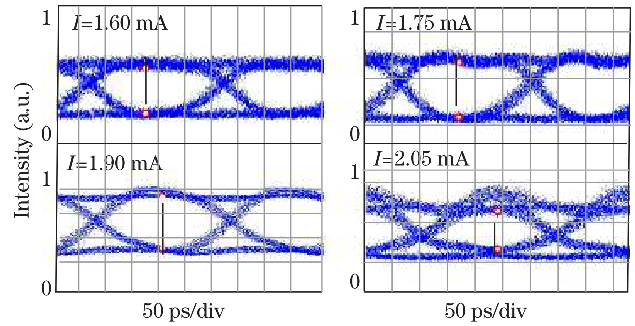

Fig. 4. Eye diagrams of the 2.5-Gb/s PRBS signal at four bias currents.

bandwidth. However, with the bias current increasing, the gain bandwidth of the VCSEL becomes narrow, and a sharper spike of the gain spectra emerges. These changes easily lead to uneven delay spectra with narrow bandwidth, resulting in degraded signal quality. Note that the VCSEL used in our experiment is a commercial laser similar to that used in previous experiments[9−12] and is not designed for use as an amplifier. Therefore, optimizing the structure for flattened gain profiles may be promising for VCSELs to meet the practical requirement in the future.

As a micro cavity device, gain saturation is a key issue in the VCSEL. The origin of the saturation lies in the power dependence of the gain. Increased input signal power causes carrier depletion, resulting in the gain reduction, and shorter slow light delay is expected in the VCSEL according to the discussion on Fig. 3. Figure 5 shows the experimental results of the 2.5-Gb/s PRBS delay varying with input light power. Aside from the increased light power, the dominant contribution to the clearer opening eye diagram comes from the wider gain bandwidth under larger input signal power, as discussed in Fig. 4. By increasing the signal power, the peak gain wavelength of the VCSEL shifts toward the short-wavelength range. This shift of peak gain wavelength destroys the signal resonance with the VCSEL when the input light wavelength is fixed and degrades the signal quality. The results are shown in Fig. 6. Although the input signal is tuned to track the peak gain

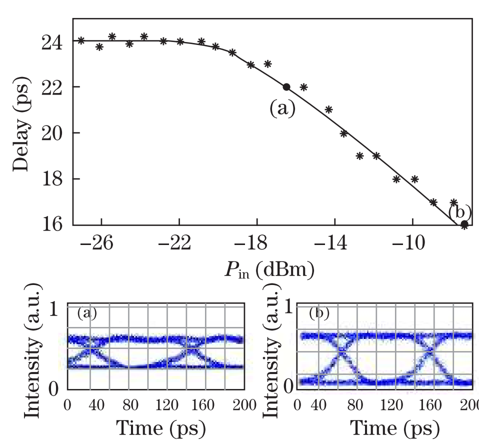

Fig. 5. Delay of 2.5-Gb/s PRBS versus input power with 1.75-mA bias current. Insets (a) and (b) show the eye patterns at the signal powers of –16.5 and –7.4 dBm, respectively.

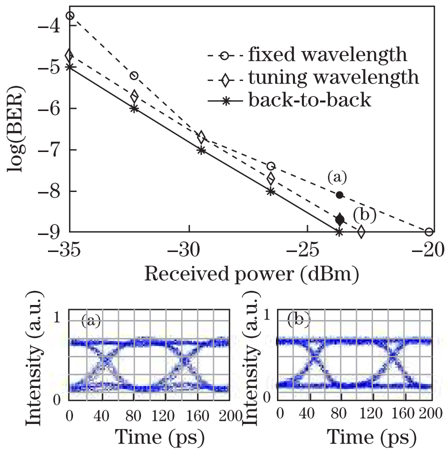

Fig. 6. BER of 2.5-Gb/s output signal versus input power with 1.75-mA bias current. Insets (a) and (b) show the eye patterns at a fixed wavelength and tuning wavelength, respectively.

wavelength of the VCSEL, the BER of the slow light is evidently lower than the case of a fixed signal wavelength. Although the signal wavelength change has an effect on the peak gain wavelength, in the experiment, we carefully controlled the signal wavelength to coincide with the peak gain wavelength of the VCSEL to reduce this resonance detuning. Under such circumstances, a power penalty as low as 1 dB was achieved in our experiments. To the best of our knowledge, this is the first time the BER of PRBS delay in VCSELs has been shown. This implies that the VCSELs have potential application as compact optical buffers. Thus, developing new methods, such as designing a new cavity structure[15] or optimization to become an optical amplifier[13], is necessary to improve the gain bandwidth of VCSELs to have a good trade-off between the bandwidth and the delay.

In conclusion, a tunable slow light of 2.5-Gb/s PRBS signal is performed using a 1550-nm QW VCSEL. The experimental results show that the optical delay of 98 ps is achieved by the increase in bias current. With the signal intensity changing, variable optical delays between 16 and 24 ps are obtained. Although it operates as a VCSEL amplifier, the VCSEL has good power potential as a slow light device. However, for its application in practical communication systems, the VCSEL should have gain and time delay as flat as possible over all the input signal bandwidths, which may be achieved by designing a special cavity structure[15] or being optimized as an optical amplifier[13].

The work was supported by the Fundamental Research Funds for the Central Universities of China under Grant No. SWJTU09ZT14. The authors would like to thank Dr. Guangqiong Xia of Southwest University for providing the VCSEL.

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