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Electrically and Continuously Tunable Optical Delay Line Based on a Semiconductor Laser

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This investigation experimentally demonstrates the feasibility of the electrically and continuously tunable optical delay line using a semiconductor laser. The time delays for a 10 Gbps data signal are electrically delayed by adjusting the bias current of laser, and the maximum delay is approximately 41 ps. We also measure the bit error rate against the receiver power by various bias currents and wavelength detuning ($\Delta\lambda$). Measurements are made to verify the feasibility to use in optical communication systems.

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1. Introduction

In recent years, tunable optical delay lines have become a streamline technology in a number of applications including packet synchronization, optical buffer, microwave signal processing, optical communication and phase-array antenna systems.[1–7] Recently, optical fiber delay lines based on re-circulating, feed-forward, or folded-path structures have been proposed.[6,7] However, several defects remain to be eliminated, such as bulkiness, complexity and inability to be electrically tuned.

The investigations of optical delay lines based on slow light have attracted considerable attentions and interests.[3–5] Moreover, research on delay line is currently focused on designing all-optical devices that are compatible with high-speed optical communication systems. Recently, optical delay lines based on semiconductor optoelectronics have attracted substantial interest due to their compactness, smallness, lightness and ease of integration.[8,9] Furthermore, the theoretical model for the slow light in a vertical-cavity surface-emitting laser (VCSEL) was reported.[10] However, an electrically and continuously tunable optical delay line that is based on slow light in a VCSEL for high-speed optical communication systems has not yet been investigated.

In this paper, we propose a tunable optical delay line that is based on slow light in a VCSEL for 10 Gbps optical communication systems. Delays are tuned by adjusting the bias current of the VCSEL and time delay of 10 Gbps data signal using electrically controlled of VCSEL is experimentally demonstrated. The relationship between the time delay and the bias current of the VCSEL is examined. The bit error rate is also measured against the received power for variously delayed signals by various bias currents and wavelength detuning ($\Delta\lambda$). The results of the experiment show that the optical delay line can be used for high-speed optical communication systems.

2. Experiment and Results

Figure 1 shows the experimental setup for measuring tunable delays in a quantum well VCSEL. An optical signal is generated by a laser source and modulated using a Mach–Zehnder modulator (MZM). A 10 Gbps non-return-to-zero pseudo-random binary sequence signal (pattern length $2^7 - 1$) is fed into the MZM. An optical circulator (C) is utilized to couple the optical signal into the quantum well VCSEL. A polarization controller (PC) is used to get maximum interaction between the probe signal and VCSEL. An optical coupler splits the output signal from the circulator output into two paths. One is sent to an optical spectrum analyzer (OSA) and another is sent to a 10 Gbps lightwave receiver. Finally, the time delay and the bit-error-rate (BER) are measured using an oscilloscope and an error detector, respectively.

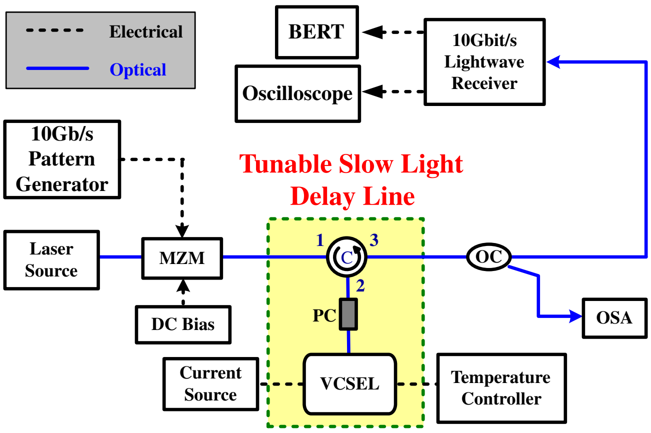

Fig. 1. (Color online) Experimental setup (MZM: Mach–Zehnder modulator, C: optical circulator, OC: optical coupler, PC: polarization controller, OSA: optical spectrum analyzer, BERT: bit error rate test, VCSEL: vertical-cavity surface-emitting laser).

Figures 2 and 3 display the output spectra and the light-current characteristics of the quantum well VCSEL. The quantum well (QW) VCSEL (InAlGaAs/InP QWs) is a commercial product. The threshold current is about 1.7 mA ($I_{th} = 1.7$ mA), and the lasing wavelength is around 1538.45 nm. The output spectra are adjusted by varying the bias current from 1.3 to 1.8 mA as shown in Fig. 2. The lasing wavelength is shifted to longer wavelengths by increasing the bias current.

Figure 4 present the measured time delays for a 10 Gbps non-return-to-zero signal under various bias currents. The reference signal is directly reflected from the top mirror of

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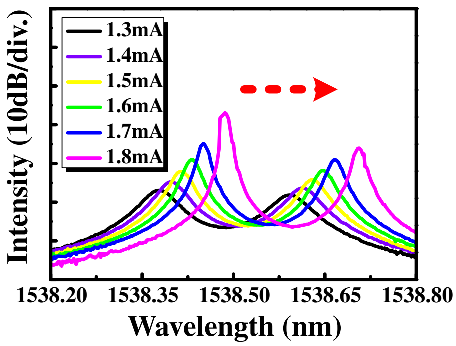


Fig. 2. (Color online) Output spectra of QW VCSEL.

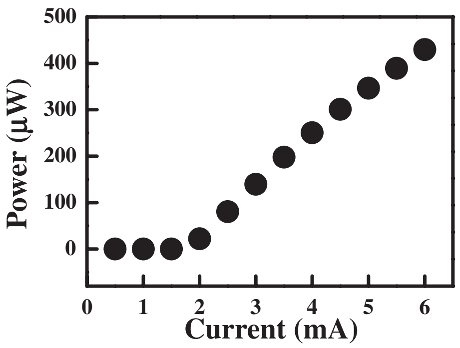


Fig. 3. Light-current characteristics of QW VCSEL.

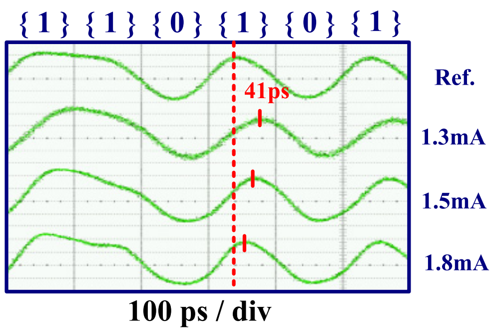


Fig. 4. (Color online) Measured time delays by various bias currents of quantum well VCSEL.

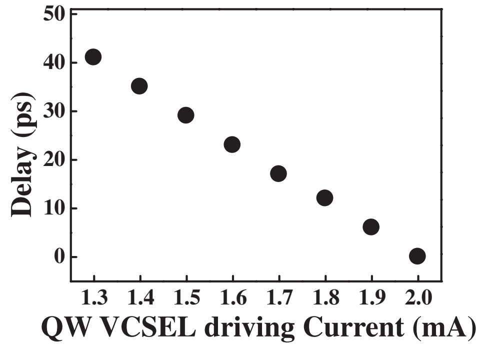


Fig. 5. Relationship between the time delays and the bias currents of quantum well VCSEL.

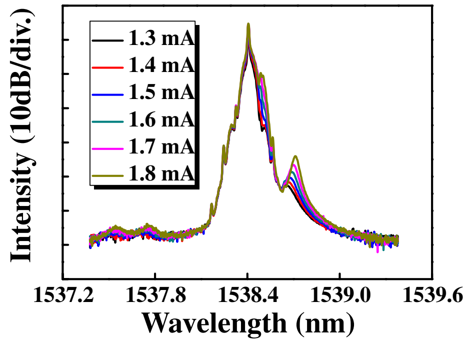


Fig. 6. (Color online) Output spectra of tunable delay line by various bias currents.

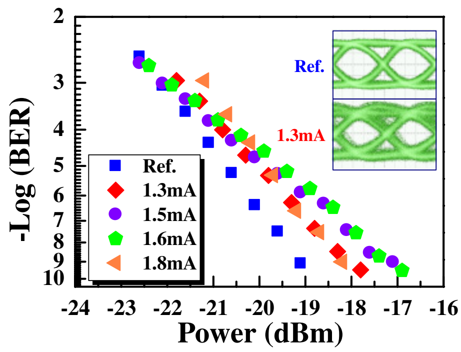


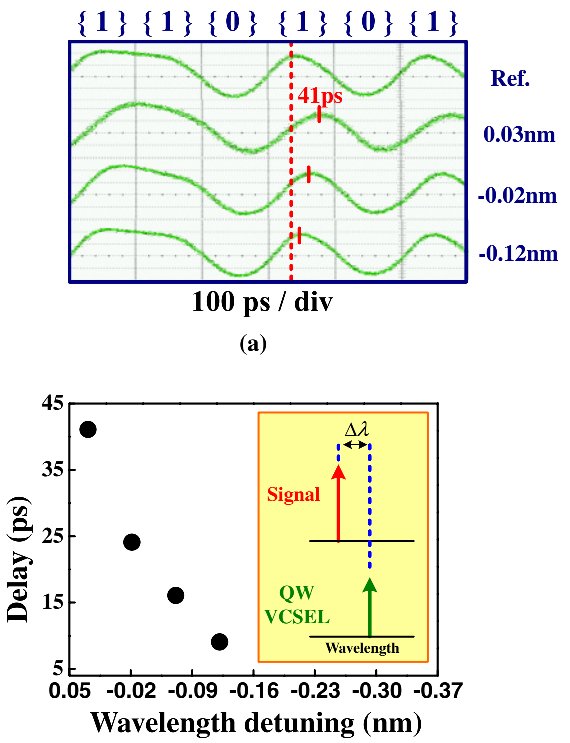
Fig. 7. (Color online) Measured bit error rate (BER) curves by various bias currents of VCSEL.

the VCSEL. The injection power of the probe signal is about −6 dBm. Increasing the injection power will vary the gain in the VCSEL. The maximum optical delay of about 41 ps is observed, when the bias current is 1.3 mA. The delay-bandwidth product is approximately 0.41. The optical delay line can be electrically tuned by varying the bias current. The relationship between the time delay and the bias currents of the quantum well VCSEL is plotted in Fig. 5. The measured time delay increases linearly with the bias currents of the quantum well VCSEL. These results indicate that the delay for 10 Gbps data signal in a VCSEL can be electrically and continuously controlled.

Figure 6 show the output spectra of the delay line. The wavelength of the probe signal is fixed at 1538.41 nm and the bias current of the quantum well VCSEL is varied from 1.3 to 1.8 mA. The device operates at a single optical wavelength and is not influenced by variation of the bias current.

Figure 7 plots the measured bit error rate as a function of the received power at various bias currents of the quantum well VCSEL. The bit error rate measurements reveal that the slow light delay line is suitable for a 10 Gbps data signal. The signal is degraded because of the narrow bandwidth of the VCSEL. The inset in Fig. 6 display eye diagrams at bias current of 0, 1.3 mA. The eye diagrams of the slow light delay line are clear.

The delay at different wavelength detuning values $\Delta\lambda$ is also examined ($\Delta\lambda = \lambda_{\text{Probe}} - \lambda_{\text{VCSEL}}$, the difference between the wavelength of the probe signal and that of the lasing wavelength of VCSEL). Figure 8 plots the measurement of time delay at various wavelengths detuning $\Delta\lambda$ when the driving current is 1.3 mA and the lasing wavelength 1538.38 nm. Figure 8(a) plots the waveforms



(b)

Fig. 8. (Color online) Measured time delays by wavelength detuning ($\Delta\lambda$).

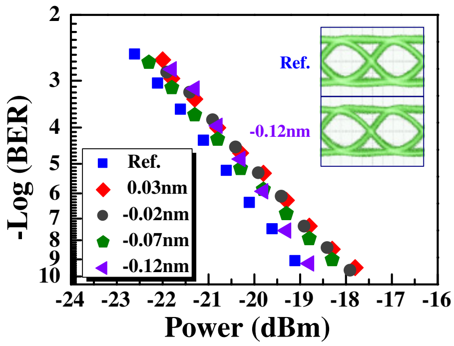


Fig. 9. (Color online) Measured bit error rate (BER) curves obtained by wavelength detuning ($\Delta\lambda$).

when the wavelength detuning values are 0.03, -0.02, and -0.12 nm, respectively. Figure 8(b) summarizes the temporal shift that is associated with wavelength detuning $\Delta\lambda$ and shows an optical delay of 41 ps delay at a wavelength detuning 0.03 nm. Figure 9 plots the performance of the proposed slow light delay lines at various wavelength values. The power penalty is less than 2 dB. The above results experimentally demonstrate that a slow light delay line based on a semiconductor laser for a 10 Gbps data signal can be applied in a 10 Gbps system. In the experiment, we observe that the power penalty increases as the pattern length increases from $2^7 - 1$ to $2^{31} - 1$. Such data degradation could be caused by the slow-light-induced pattern dependence and the carrier lifetime. The slow-light-induced pattern dependence is identified as a main reason for data degradation, which is caused by the narrow-band amplitude and phase responses of the slow light element.[11] Therefore, detuning the gain peak of the slow light element away from the wavelength of the probe signal can reduce the pattern dependence.[11] Furthermore, the response speed of VCSEL is governed by the carrier lifetime. Hence, a high speed VCSEL in the system would reduce data degradation.

3. Conclusions

This investigation experimentally demonstrates the feasibility of an electrically controlled tunable delay line using a semiconductor laser at room temperature with 10 Gbps non-return-to-zero pseudo random binary sequence data. The tunable time delays can be tuned by varying the bias current of the quantum well VCSEL; the maximum delay is about 41 ps. The BER measurements demonstrate that the tunable optical delay line can be applied in a 10 Gbps optical communication system. Furthermore, this optical delay line can be further developed not only to reduce size and cost but also for application to microwave signal processing.

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