Nanosecond-scale Hitless λ-switching of SOA-integrated Electro-optically Tunable RTF Laser with +/-2.5-GHz Dynamic Frequency Accuracy

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Abstract: We developed an SOA-integrated electro-optically tunable RTF laser with suppressed spurious wavelengths during dynamic tuning. The laser exhibited hitless (no interference with other channels) nanosecond-scale λ-switching for 128-Gbps coherent signals.

OCIS codes: (130.0130) Integrated optics devices; (130.4815) Optical switching devices; (140.3600) Lasers, tunable

1. Introduction

Optical switching is a promising way to reduce the number of power-hungry and large-latency electrical switches in data center interconnections [1, 2]. It also plays an important role even in evolving computer architectures with disaggregated hardware resources (processer, memory, accelerator, etc.) connected to each other through a large bandwidth optical link [3]. A tunable laser diode (TLD) with nanosecond (ns)-scale wavelength switching (λ-switching), low tuning power dissipation (P_{tune}) and narrow linewidth is a key device for such optical switching systems. We have developed an electro-optically tunable reflection-type transversal filter (RTF) laser [4-6] that meets above requirements for a TLD thanks to the nature of the electro-optic (EO) effect as the tuning mechanism.
In this paper, we describe a progressed RTF laser with monolithically integrated semiconductor optical amplifier (SOA) as an optical shutter for hitless λ-switching (switching one λ-channel without interfering with other channels.) The SOA is dynamically turned OFF/ON to eliminate laser outputs with spurious wavelengths during tuning which degrade communication quality in corresponding wavelength channels (λ-channels). We confirmed that, unlike in conventional SOA-integrated TLDs [7], there is little fluctuation of the laser frequency during the SOA-shutter operation. This is because the ns-scale λ-switching of the EO effect-based RTF laser requires a corresponding ns-scale SOA-shutter time which is much faster than the thermal-crosstalk response from the SOA to the RTF-laser cavity. As a result, the thermal-crosstalk response has little influence on the lasing frequency. Using the laser, we successfully demonstrated ns-scale hitless λ-switching for 128-Gbps coherent signals.

2. Static performance of SOA-RTF laser

Figure 1 shows a schematic of an SOA-integrated RTF laser (SOA-RTF laser). The laser consists of an active section (ACT) for cavity gain, and an SOA connected to the ACT, and an RTF as a tunable filter. While the ACT and SOA are made of the same multi-quantum well (MQW) with an optical gain, the RTF is made of an MQW for the quantum-confined Stark effect (QCSE). The RTF is composed of a 1 x 5 multi-mode interference coupler (MMI) and five reflection-type delay lines terminated with Au mirrors. The length of each delay line determines the reflection spectrum the RTF. The RTF has four tuning electrodes to which reverse voltages are applied for the QCSE. Two comb-shaped electrodes formed on three of the five delay lines are used for coarse tuning with red and blue shifts. An electrode formed on the longest delay line and one formed on the 1 x 5 MMI are used for fine and phase tuning, respectively. The spectral shift of the coarse and fine tuning for a given applied voltage depends on the tuning electrode length. This means that the tuning efficiency of the RTF can be designed independently of the EO coefficient of the QCSE. As a result, a practical tuning range is obtained even with the QCSE, whose amount of reflective index change is ~1/10 that of conventional tuning mechanisms such as the carrier injection and thermo-optic effect. The tuning voltages applied to the coarse and fine electrodes and the corresponding lasing spectra are shown in Fig. 2(a) and (b), respectively. The ACT current and chip temperature were 50 mA and 45°C for all experimental results shown in this paper. Phase tuning voltages were applied so that each lasing wavelength fits a target λ-channel. The laser covers over 35-nm wavelength range with absolute tuning voltages of less than 15 V. The corresponding P_{tune}, defined as the total of the products of applied voltages and photo currents, is less than 50 mW as shown in Fig. 2(c). The P_{tune} of the RTF laser is mostly derived from the electrostatic energy (photo-carrier

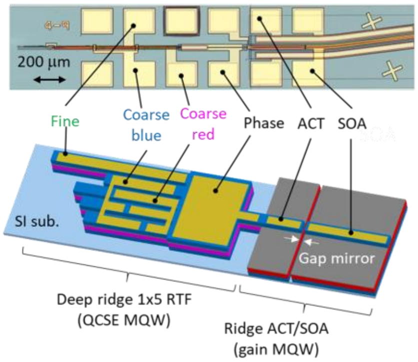

Fig. 1. Schematic of SOA-RTF laser.

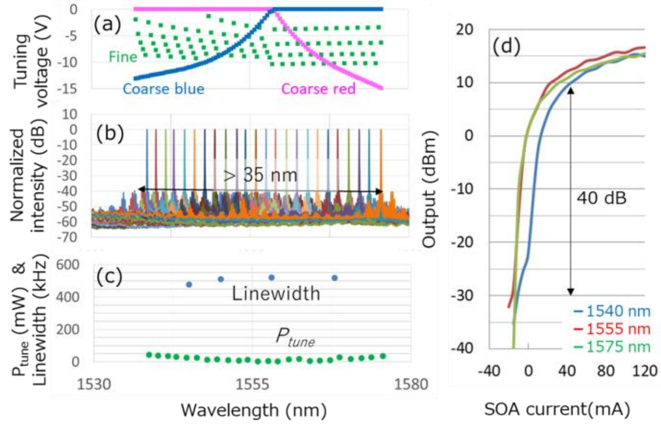

Fig. 2. Static performance: (a) tuning voltage; (b) lasing spectra (200-GHz interval); P_{tune} and linewidth; (d) optical output.

extraction) rather than from the thermal energy. Therefore, it hardly changes the chip temperature, resulting in little thermal drift in λ-switching [8] compared to that in a current-injection type TLD. The effective linewidth measured from the frequency noise of the laser is ~500 kHz [Fig. 2(c)] which is acceptable for conventional 100G coherent systems described in the next section. It is narrower than that of a carrier-injection-type TLD, which suffers from linewidth broadening due to free-carrier-induced noise. The linewidth of the SOA-RTF laser could be further reduced by improving the anti-reflection coating at the chip facet because of a narrower linewidth of our conventional RTF laser without an SOA. We confirmed output of ~+15 dBm from the laser with wavelengths covering 35 nm [Fig.2 (d)]. Even if we assume optical assembly loss of over 1 dB, the output is still larger than the +13 dBm required for a long-haul light source [9]. We also found that 40-dB extinction ratios (ERs) are obtained regardless of the laser wavelength. The large ERs without wavelength-dependent bias control are beneficial for a TLD emitting light with various wavelengths when we consider the shutter performance of the SOA.

3. Hitless λ-switching with high-frequency accuracy using high-speed SOA-shutter operation

The generation of spurious wavelength from a TLD during λ-switching is an issue in optical switching since they are seen as crosstalk by other λ-channels. Figure 3(a) and (b) show wavelength-time (λ-time) maps of an SOA-RTF laser performing eight-λ-channel switching with and without SOA-shutter operation, respectively. The applied voltages from a function generator to the SOA for the ON and OFF states were 1.5 V (~70 mA) and -0.5 V, respectively. The λ-switching time was ~30 ns, which was limited by the bandwidth of the four-channel arbitrarily waveform generator (AWG) supplying the tuning voltages to the four tuning electrodes. While spurious wavelengths appear at the time of λ-switching without SOA shutter operation, they are eliminated with an over 30-dB dynamic ER (measurement limit) by dynamically turning OFF the SOA [Fig. 3(c) and (d)]. The longer SOA-shutter time of 50 ns [Fig.3(e)] than the λ-switching of 30 ns comes from the through rate of the SOA response, which can be further reduced by employing a higher-speed current driver and/or optimizing the supply current waveforms [10].

Although use of the SOA shutter is a viable approach for hitless operation, an issue is laser-frequency drift after the SOA is turned ON due to the low-speed thermal crosstalk from the SOA to the laser cavity. However, when it comes to the SOA-RTF laser, we can ignore the thermal drift because the ~30-ns λ-switching of the RTF laser requires a corresponding ns-scale SOA shutter operation, as shown in Fig. 3(e), which is much faster than the response time of the μs-order thermal dynamics. To examine the concept, we measured the frequency transition of the SOA-RTF laser with the SOA shutter operation using a chirp analyzer [Fig. 4(a)]. Even just after SOA is turned ON, the frequency error is in the +/- 2.5-GHz region required for practical TLDs [9], and it immediately converges to zero. Figure 4(b) shows the frequency transition when the SOA is modulated with a 1-kHz square pulse (SOA: OFF/ON = 500/500 μs). The four EO-tuning electrodes of the RTF are not modulated (0 V) in the experiment. Here, a frequency error larger than that for the 50-ns SOA shutter is observed. The frequency error decreases (wavelength increases) for ~50 μs after the SOA is turned ON. The slow response is due to the thermal crosstalk from the current-injected SOA to the laser cavity. These results indicate that the ns-scale SOA shutter is effective for eliminating spurious wavelengths without fluctuation of the laser frequency.

We also demonstrated hitless λ-switching using the SOA-RTF laser. We input laser outputs from the SOA-RTF laser operating with the same eight-channel-λ switching as in Fig, 3(a) and a monitor laser (1566.75 nm) to an optical modulation analyzer (OMA), as shown in Fig. 5(a). Each laser output was externally modulated with 32-Gbd

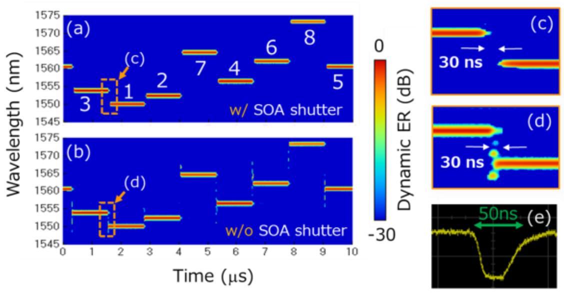

Fig. 3. λ-time map of eight-λ-channel switching (a) with and (b) without SOA shutter. (c) and (d) Corresponding enlarged views. (e) SOA response.

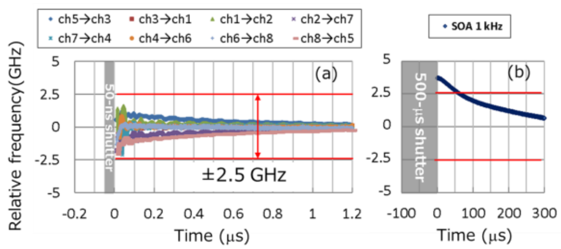

Fig. 4. Frequency response in λ-switching with (a) 50-ns SOA shutter and (b) SOA 500-μs shutter.

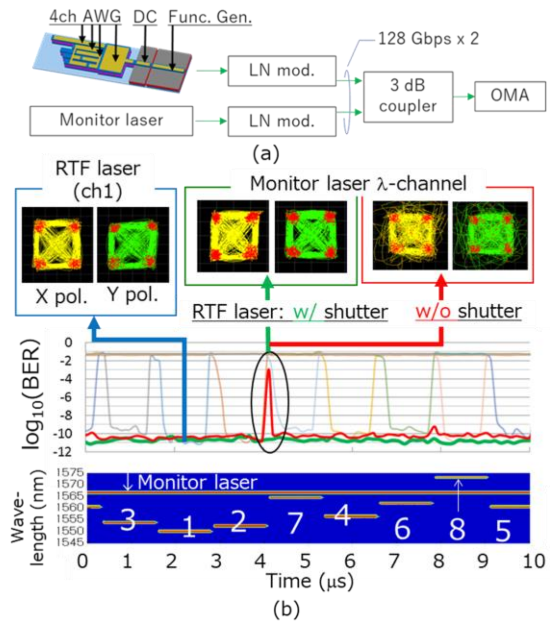

Fig. 5. Hitless λ-switching: (a) Measurement setup. (b) Dynamic BER and corresponding consternation maps for X and Y polarization (pol.) channels .

dual-polarization quadrature phase shift keying by a commercially available lithium niobate (LN) modulator. Figure 5 (b) shows dynamic bit-error rates (BERs) estimated from corresponding constellation maps. In the experiment, the optical signal-to-noise ratio of each λ-channel, including the monitor one, was set to about 30 dB. We confirmed dynamic BERs of less than 10^{-9} in all eight λ-channels of the dynamically tuned SOA-RTF laser, which indicates the high-speed and narrow-linewidth nature of the laser. While the dynamic BER of the monitor-laser signals obviously degrades at the time of switching the λ-channel from ch2 to ch7 *without* the SOA shutter operation, the degradation disappears *with* the SOA shutter operation, namely, hitless λ-switching is successfully demonstrated.

4. Conclusion

We developed an SOA-RTF laser with larger than +13-dBm optical output for 35-nm wavelength range. The SOA is used to eliminate spurious wavelengths during dynamic tuning with +/- 2.5GHz frequency error even just after λ-switching. We also demonstrated hitless eight-channel λ-switching of the SOA-RTF laser for 128-Gbps coherent signals without interference with monitor λ-channel signals. The SOA-RTF laser with hitless ns-scale λ-switching available for coherent formats is beneficial for constructing future optical future switching systems for data center interconnections and disaggregated computers.

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