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Switching dynamics of DS-DBR laser under optical injection locking to achieve fast optical switching with enhanced coherence

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Wavelength switching is a promising candidate for future optically switching flat data center network due to its high scalability. The wavelength switching latency of a tunable laser must be maintained within few nanoseconds to ensure high network throughput, because data center IT traffic is dominated by small-sized packets (e.g., hundreds of ns). In addition to this, the increasing data capacity demand has triggered the need for coherent transmission in next-generation data center interconnection. As a result, tunable laser must simultaneously feature low linewidth and fast switching time. However, these two requirements are inherently contradictory, as narrow linewidth requires laser designs to achieve a long photon lifetime, while fast switching requires a short photon lifetime. We demonstrate using the optical injection locking (OIL) technique to improve the phase noise of a ns-scale switching digital supermode (DS) distributed Bragg reflector (DBR) laser. With −24 dBm injection power, we show that DS-DBR laser coherence is significantly improved, with linewidth performance following seed laser (≤15 kHz). With optical injection locking, the switching latency is also slightly improved, with ≤5 ns for both rising and falling edges.

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Introduction. The rapid increase of data traffic in data center (DC) networks has motivated fast optical switching as a viable approach to overcome DC networks' scalability bottleneck due to port number and bandwidth (BW) limitations in conventional all-electronic switches [1]. Additionally, optical switching enables a more flat network architecture that can potentially reduce power consumption and end-to-end latency for green and high-throughput DC networks, fulfilling the long-term goal of a green global communication infrastructure [2–4].

To this end, fast wavelength switching emerges as a promising technique to facilitate future DC networks due to its low loss and high scalability [3] and has motivated several recent research on wavelength-switched transceivers with nanosecond-level switching time. For example, in [4], researchers propose a semiconductor optical amplifier (SOA) array-based switch to select and amplify individual wavelengths from a frequency comb source, with a demonstration of sub-nanosecond (ns) switching over 19 wavelengths. However, the power consumption of such a scheme scales drastically with the number of wavelengths and is power hungry due to the SOA array. The relatively low power per tone and the high noise figure resulted in an optical-signal-to-noise ratio of less than 30 dB, fundamentally limiting the bit error ratio and the achievable data rate [4]. Compared to SOA array-based approaches, wavelength-tunable lasers have been actively studied to achieve ns-scale wavelength switching with a smaller chip area and lower power consumption. A variety of lasers have been studied, including digital supermode (DS) distributed Bragg reflector (DBR) laser [2,5], dual-ring resonators Vernier configuration Fabry–Pérot laser [6], and reflection-type transversal filter-based tunable laser [7]. By optimizing the driving signal to switch the DS-DBR laser, researchers have demonstrated less than 10 ns switching time across 6 THz in telecom C band [5]. The measured switching time of dual-ring resonators Vernier configuration Fabry–Pérot laser and reflection-type transversal filter-based tunable laser are 2 ns and 0.5 ns, respectively [6,7].

Besides switching time, a higher data rate exceeding 1.6 Tb/s is required for server-to-server data communication [8], triggering research into optically switched coherent communications that require light sources to be simultaneously low linewidth and fast switchable. These two requirements, however, are inherently contradictory as narrow linewidth requires laser designs to achieve a long photon lifetime and low driver bandwidth (for low thermal noise), while fast switching requires a short photon lifetime for fast carrier-photon response and high driver electronic bandwidth. One potential solution, as recently demonstrated in [6], is to balance the linewidth and switching time requirements. This study shows a dual-ring-resonator laser in a Vernier configuration, achieving a fundamental linewidth of about 400 kHz and a switching time of 4 ns, demonstrating up to 32 GBd DP-16QAM (200 Gb/s/λ in the payload) wavelength-switched coherent transmission.

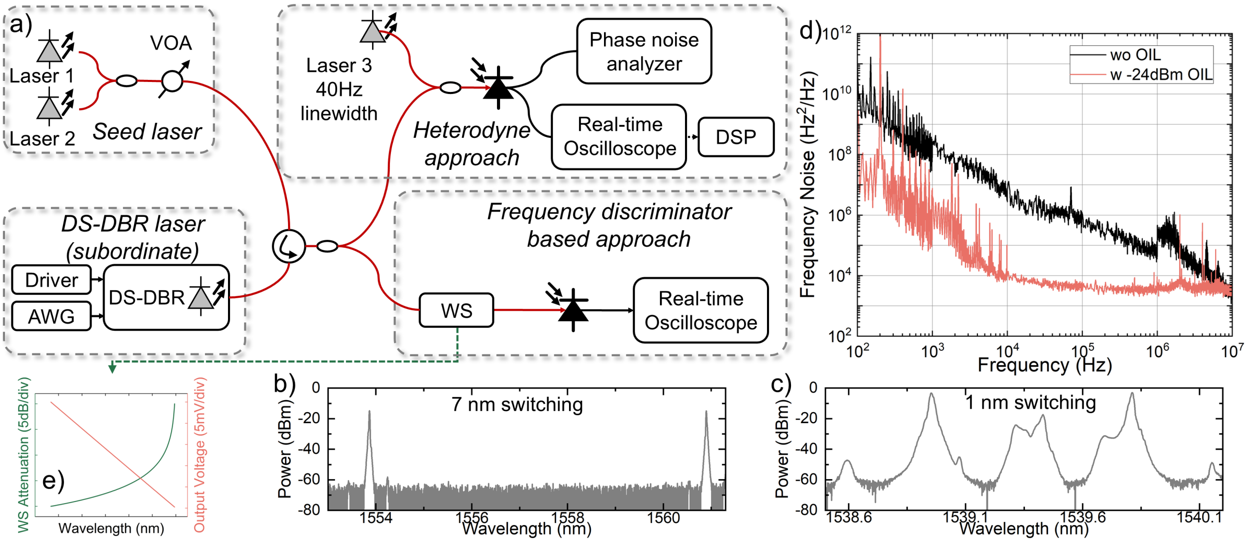

Fig. 1. (a) Experimental setup, wavelength switching optical spectrum for (b) 7 nm switching pair, (c) 1 nm switching pair, (d) measured frequency noise of DS-DBR laser with and without OIL under CW operation, and (e) conceptual waveshaper response. AWG, arbitrary waveform generator; DSP, digital signal processing; VOA, variable optical attenuator; WS, waveshaper.

Previously, optical injection locking (OIL) has been exploited to improve the linewidth of fundamentally noisy lasers [9] with a simultaneous reduction in relative intensity noise (RIN) and turn-on delay of locked lasers with the photon–photon interaction [10]. By seeding a DS-DBR laser with a frequency comb, the continuous-wave (CW) operating laser showed significant linewidth reduction from 2 MHz to 4 kHz with a high OSNR, demonstrating coherent modulation using DP-64QAM [11]. However, to the best of the authors' knowledge, the dynamic behavior of a wavelength-switching DS-DBR laser under OIL, such as switching time, frequency, and phase variation, has not been studied. Thus, whether such a scheme (OIL to DS-DBR laser) could be used for wavelength-switched coherent transceivers was unknown.

In this paper, we systematically investigate the switching dynamics of a DS-DBR laser injection locked by two CW wavelengths, with the DS-DBR laser driven by a high-speed waveform for switching. To study the impact of OIL on switching time and laser coherence, we used two approaches—frequency discriminator and coherent beating—to investigate the frequency variation of the locked laser in both switching and steady states. We experimentally demonstrate that an injection-locked DS-DBR laser exhibits the same phase noise performance as the seed laser (with linewidth of <15 kHz) at a switching time of 5.5 ns under a relatively low injection power of −24 dBm, validating its suitability for wavelength-switched coherent transceivers.

Experimental setup. Figure 1(a) shows the experimental setup. A DS-DBR laser outputs 12 dBm CW with its front grating and gain sections driven by constant current sources, and its rear grating is driven by an 8-GHz-bandwidth arbitrary waveform generator (Tektronix 70002 A) for switching. The DS-DBR is a standard iTLA module with its isolator removed to facilitate OIL [11,12].

The AWG outputs a square waveform of 5 MHz repetition rate to drive the rear grating of the DS-DBR laser, resulting in a wavelength switching at 100 ns intervals. In this study, we tested two wavelength pairs of 7 nm (1554–1561 nm) and 1 nm (1539–1540 nm) spacing. These two switching pairs are specifically chosen to represent two typical switching dynamics of the DS-DBR laser. When the rear grating voltage increases linearly, the DS-DBR laser wavelength continuously tunes over 1 nm, but exhibits wavelength hopping for the 7-nm switching pair (as shown in Supplement 1). The measured optical spectra for both switching pairs are shown in Figs. 1(b) and 1(c), for the 7-nm-spacing pair and the 1-nm-spacing pair, respectively.

In this proof-of-concept experiment, we used two external cavity lasers (Pure Photonics PPCL550, i.e., laser 1 and laser 2) as seed lasers. The seed lasers are tunable across 1528 to 1565 nm, with 60 dB OSNR (0.1 nm bandwidth) and 15 kHz measured linewidth (considering 100 μs observation time [13]). Both lasers output the same power and are combined by a 50/50 polarization-maintaining (PM) coupler before injecting into the front facet of the DS-DBR laser module via a PM circulator. A variable optical attenuator (VOA) is used to adjust the injection power. The seed lasers could be replaced by a frequency comb source to facilitate OIL of multiple wavelengths, as previously demonstrated in [11]. Figure 1(d) shows the measured frequency noise of the DS-DBR laser with (red curve) and without OIL (black curve) under CW operation. Both curves were measured using the self-homodyne method [13]. The CW linewidth of the DS-DBR laser significantly reduced from 1 MHz to 13 kHz.

We employed two approaches to study the frequency variation in the wavelength switching and steady-state periods: a frequency discriminator-based approach that offers a large dynamic range but limited resolution, and a heterodyne approach that has a lower dynamic range but high phase/frequency resolution. The frequency discriminator approach uses a waveshape with a linearly increased loss over wavelength to form a linear frequency discriminator for the switching wavelength pairs. As shown in Fig. 1(e), the long wavelength is linearly attenuated by a factor of 100 (20 dB) compared to the short wavelength, providing a dynamic range of 20 dB for different wavelength pairs. The output of the waveshaper is detected by a 5-GHz-BW photodetector (PD) before being captured by a 25-GSa/s

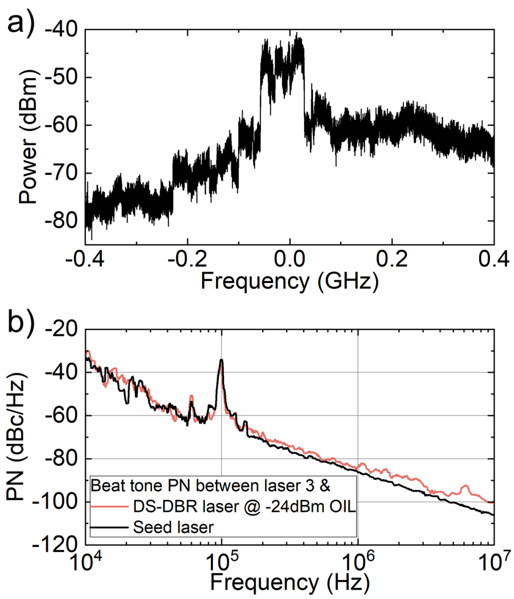

Fig. 2. (a) PSD of beat tone between DS-DBR and laser 3 under steady-state operation for 1554–1561nm switching pair without injection and (b) phase noise of beat tone between laser 3 and injection-locked DS-DBR laser/seed laser.

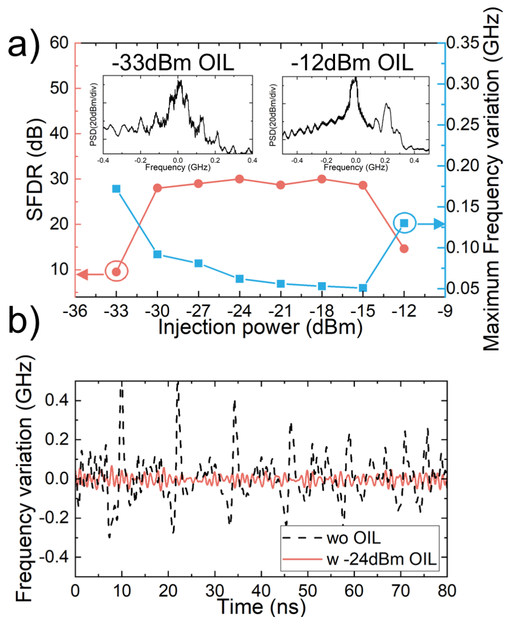

Fig. 3. (a) Measured SFDR of beat tone between DS-DBR laser and laser 3 and corresponding maximum frequency variation under steady-state operation and (b) calculated frequency variation of beat signal between DS-DBR laser and laser 3.

real-time oscilloscope with 8-bit resolution. The frequency resolutions for 7 nm and 1 nm switching pairs are 4.9 and 0.7 GHz, which are determined by the dynamic range of waveshaper and oscilloscope.

The heterodyne approach employs an ultra-low noise laser (laser 3) with a linewidth of 40 Hz emitting at 1553.97 nm as a local oscillator to beat with the DS-DBR laser's output on the 5-GHz-BW PD. The 40-Hz linewidth laser is a whispering-gallery-mode-resonator-based external-cavity semiconductor laser (OE4023) [14]. The output of PD is connected to a phase noise analyzer for beat tone frequency spectrum and phase noise measurement. The phase and frequency variation measurement is done by capturing time-domain waveform followed by offline digital signal processing (DSP). The beat tone signal is digitally down-converted to the baseband. A 1-GHz digital filter is employed to limit the noise bandwidth to less than 1 GHz. This approach offers a dynamic range of $\pm$ 0.5 GHz but a fine frequency resolution of 10 MHz, permitting studying frequency noise and phase coherence during switching and steady state.

Results. We first characterize the steady-state performance of the DS-DBR laser switching between 1554 nm and 1561 nm. Figure 2(a) shows the spectrum of the beat signal between laser 3 and the free-running DS-DBR laser (normalized to baseband) when switching to 1554 nm. The broad beat signal BW is primarily due to 1) the inherently large linewidth of the DS-DBR laser and 2) frequency variation. With −24 dBm (per wavelength) OIL power, the beat note BW is significantly improved with a slight shift of the wavelength. Figure 2(b) shows the measured phase noise of beat tone. The red and black curves represent the beat tone between laser 3 and injection-locked DS-DBR laser (with −24 dBm OIL) and seed laser, respectively. At 10 kHz and 1 MHz frequency offset, the measured phase noises are −30 dBc/Hz and −85 dBc/Hz for both curves, indicating that the wavelength switching injection-locked DS-DBR laser follows the same phase noise performance as seed laser.

Further increasing the injection power leads to harmonic peaks due to the non-linear laser dynamics under OIL [15], making the laser unsuitable for coherent communications. To study the optimal injection power, we increase the injection power from −33 dBm to −12 dBm, and measure the spurious free dynamic range (SFDR) of the beat signal to show the performance. As shown in Fig. 3(a), the SFDR increases from 9 dB to 30 dB when OIL power increases from −33 to −24 dBm, and it starts to decrease with OIL power higher than −15 dBm. The insets in Fig. 3(a) show the measured RF spectra of the beat signal with −33 dBm and −12 dBm OIL power. Multiple high-frequency harmonic tones also show up due to the nonlinear mixing inside the DS-DBR laser. These results can be cross-verified by the maximum frequency variation measurement. With −33 dBm OIL power, the maximum frequency variation under steady-state operation is 170 MHz. As OIL power increases, the maximum frequency variation reduces to around 50 MHz and starts to increase again at −12 dBm OIL power due to non-linear laser dynamics. The decreased performance at low OIL power is due to the reduced locking range that leads to unstable locking. The decrease of SFDR in high-frequency region, however, is due to the nonlinearity within the DS-DBR laser under high injection power. This also indicates that we only need relatively low OIL power to achieve coherence operation of the wavelength-switching DS-DBR laser, at a trade-off of more precise wavelength control [9]. Such OIL power could be achieved by the majority of frequency comb generators without any external amplification. Figure 3(b) compares the frequency variation over 80 ns in the steady states, measured using the heterodyne method. Without OIL, the peak-to-peak frequency variation could be up to 700 MHz, while the maximum variation with −24 dBm OIL is significantly reduced to around 50 MHz.

The large frequency variation during wavelength switching is characterized by the frequency discriminator. Figures 4(a) and 4(b) show the measured frequency variation

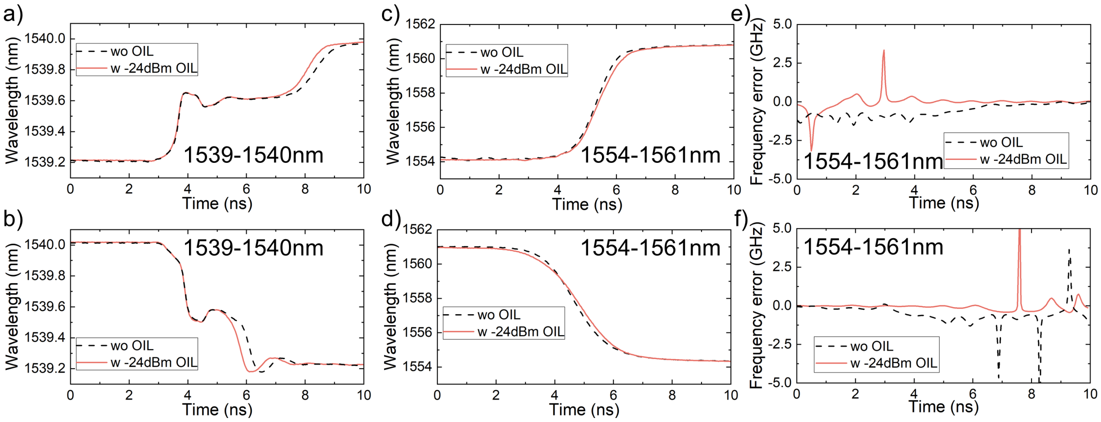

Fig. 4. Wavelength variation using frequency discriminator approach. (a) Rising edge of 1539–1540 nm switching pair, (b) falling edge of 1539–1540 nm switching pair, (c) rising edge of 1554–1561 nm switching pair, (d) falling edge of 1554–1561 nm switching pair, frequency error measurement for 1554–1561 nm switching pair at (e) rising edge and (f) falling edge.

of the 1539–1540 nm pair (a), (b), and Figs. 4(c) and 4(d) show the 1554–1561 nm wavelength pair. The dashed lines show wavelength variation without OIL, while the solid red lines show the cases with −24 dBm OIL. The power variation of the DS-DBR laser during switching was included in Supplement 1.

Without OIL, the switching times from 1539 nm to 1540 nm (the rising edge) and from 1540 nm to 1539 nm (the falling edge) are 6 and 4 ns, respectively. The switching time only slightly improved to 5.5 and 3.5 ns, respectively, with −24 dBm OIL power. For the 1554–1561 nm pair, the switching times for the rising and falling edges are 2 and 4 ns, both with OIL and without OIL cases. This result shows that, unlike conventional on-off modulation of an injection-locked laser, OIL has a limited impact on the switching time. This is probably due to the wide wavelength spacing and the small locking range. The similar switching speed also indicates that the switching time is mainly limited by the response time of the rear grating. Chirp is not observed during switching due to the following two reasons: 1) OIL largely suppresses the chirp within locking bandwidth [9] and 2) resolution of frequency discriminator-based approach is limited by waveshaper dynamic range.

Figures 4(e) and 4(f) show frequency variation of the 1554–1561 nm wavelength pair, with respect to the locked frequency, measured using the heterodyne method. For the rising edge, the frequency error stabilization time is reduced from 6 ns to 4 ns with −24 dBm OIL power. For the falling edge, the frequency error remains stable at 7 ns with −24 dBm OIL power while this value reduces to 3 ns without OIL. Note that in Fig. 4(e), the 3-GHz frequency error spurs are observed; this is because the DS-DBR laser was locked to one of the seed laser sidemodes during switching (as shown in Supplement 1). In this experiment, switching dynamics characterization is measured at constant temperature. The long-term stability under varying temperature will be investigated in a future study.

Conclusion. We study switching time, frequency, and phase coherence when a wavelength-tunable DS-DBR laser is injection-locked by external CW lasers. We found that OIL has a limited impact on the switching time in wavelength tuning but significantly improves the laser coherence. With OIL, the steady-state frequency variation reduced from 700 MHz to <50 MHz. The linewidth of the injection-locked DS-DBR laser is reduced from 1 MHz to 13 kHz, which follows the seed laser performance. Only small injection power is required to achieve strong phase coherence for fast-switching lasers, promising a strong potential of OIL-based tunable lasers for optically switched coherent transceivers. Although we demonstrate the phenomenon using a DS-DBR laser, we believe that the proposed scheme is applicable to other types of tunable lasers.

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Disclosures. The authors declare no conflicts of interest.

Data availability. No data were generated or analyzed in the presented research.

Supplemental document. See Supplement 1 for supporting content.

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