In-Phase/Quadrature Modulation by Directly Reflectivity Modulated Laser

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Abstract: We report a directly reflectivity modulated laser that generates a 50-Gbaud QPSK signal with a BER of $2.2\text{x}10^{-5}$. We believe this is the first demonstration of a coherent transmitter made from a directly driven laser. © 2020 The Author(s)

1. Introduction

Directly modulated lasers (DMLs), including vertical-cavity surface-emitting lasers (VCSELs), typically utilize the modulation of gain sections in a compact laser cavity [1-3]. They are widely employed in short-reach optical interconnects and communications, mainly due to their low cost, compact size and low RF power consumption. Nevertheless, the modulation of a laser's gain leads to intensity modulation with high chirp, and the modulation speed is limited by its relaxation oscillation frequency. The speed limitation could be overcome by modulating non-gain elements in the cavity such as the reflectivity of a distributed Bragg reflector laser [4], the intra-cavity loss [5-7], and the output coupling in a ring cavity laser [8]. In [9-12], we have proposed and experimentally demonstrated a novel non-gain-modulated laser, namely, a directly reflectivity modulated laser (DRML). The laser output is modulated through its actively tunable Michelson interferometer (MI) based mirror. The basic working principle relies on very fast modulation of the mirror's reflectivity with a speed beyond the relaxation frequency so that the gain medium is not disturbed, or very weakly disturbed. The demonstrated DRMLs [9-12] allow for high-speed modulation with low chirp, both intensity and phase modulation formats, and two or more independently modulated outputs. More importantly, the device still keeps the key benefit of traditional DMLs by requiring a low RF drive power because of short phase modulators in the MI-based mirror.

In this paper, we extend the concept of DRML to generate in-phase/quadrature (IQ) signals. A hybrid silicon/III-V DRML with two high-speed MI-mirrors on silicon is used for IQ components. 50-Gbaud QPSK (quadrature phase-shift keying) is successfully demonstrated. To the best of our knowledge, this is the first demonstration that a single laser allows for direct generation of coherent optical signals. The reported DRML paves the way for high-capacity and energy-efficient coherent transmitters.

2. Device Concept

Figure 1 illustrates the proposed device concept of an IQ transmitter based on a single DRML. The laser consists of three mirrors to form a closed cavity, shown in Fig. 1(a), two of which are dynamically tunable with high-speed operation (Mirror 1 and Mirror 2). While both these mirrors have a broadband reflection, there are two narrow-band optical filters (Ring 1 and Ring 2) before them to select the reflected wavelengths and filter out the high-speed modulated components. The reflected light signals from these two mirrors are combined by a 1x2 coupler. Maximum reflection into the gain medium occurs if the wavelengths and magnitudes of reflectivity from two mirrors are identical and the phase between them are in constructive interference. Multiple phase shifters are used to achieve this. To achieve high-speed tunable mirrors, we use a Michelson interferometric modulator (MIM) with the optical circuit shown in Fig. 1(b). The MIM is essentially a folded Mach-Zehnder modulator (MZM), which therefore allows both amplitude and phase modulation with low chirp. In [9], we demonstrated 40 Gb/s on-off keying (OOK) and 25 Gb/s binary phase-shift keying (BPSK) modulation with a single MIM in the cavity. The BPSK modulation (or in general, n-ASK) is particularly important for a coherent transmitter. In [11], we further demonstrated that it is feasible to generate two independent signals from two MIMs in the cavity. In this paper, two MIM-based mirrors in the current device function as IQ components whose output is combined with a 90-degree phase shifter to form IQ modulation.

The proposed DRML is realized in a hybrid silicon/III-V platform, where a commercial reflective SOA (RSOA) on InP is used for gain with a mirror. A silicon photonic integrated circuit (PIC) is employed for the rest of the optical cavity. The PIC is designed and fabricated on a 220-nm silicon-on-insulator platform in a commercial foundry. The RSOA and silicon PIC are butt-coupled using the AR-coated interface of RSOA to prevent reflection. On the silicon PIC, two inverted silicon tapers are used to achieve high coupling efficiency to both the RSOA and a fiber. Two thermally tunable rings with different free spectral ranges (FSRs) are used to achieve wide wavelength tunability. The FSRs in the C-band are 4.96 nm and 5.49 nm, respectively. The MIM-based mirrors comprise a 2x2 multi-mode interference (MMI) coupler, two high-speed phase modulators based on the reverse-biased *pn* junctions, two static thermal phase shifters (PSs), and two Sagnac loop mirrors (LMs). The *pn* junction length of the phase modulators is 500 µm, with an estimated junction capacitance around 100 fF. The modulation efficiency is about 2.5 V·cm. A packaged device is shown in Fig. 1(c).

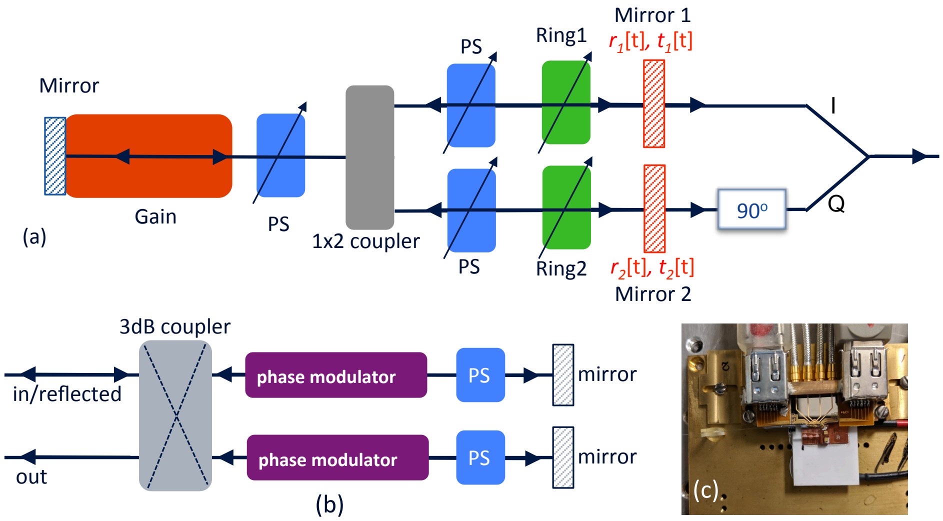

Fig. 1. DRML for coherent transmitter. (a) Optical circuit. The laser includes gain medium, a left mirror, two fast tunable mirrors (Mirror 1 and Mirror 2), two narrow-band filters (Ring 1 and Ring 2), a 1x2 coupler, and various PSs (phase shifters). (b) Optical circuit for the tunable mirrors used in (a). This is essentially a Michelson interferometric modulator (MIM). (c) Picture of a packaged DRML with a butt-coupled fiber, four-channel RF board, and various DC connections.

3. Results

The laser performance is first measured under the DC condition. We collect the spectra under different SOA currents with a spectral resolution of 0.5 nm, shown in Fig. 2(a). The threshold current is less than 50 mA and the fiber-coupled power is about -4 dBm at 100 mA. The resonant wavelengths of two rings are clearly seen in the spectra. The laser wavelength is exactly at the wavelengths at which the two rings' resonances line up. We also demonstrate the wide tunability of this DRML in Figs. 2(b) and (c) with a spectral resolution of 0.1 nm, where one of the rings is thermally tuned and the other ring has fixed resonant wavelengths. In these measurements, the SOA current is fixed at 150 mA. We achieve more than 0 dBm fiber-coupled power, a wavelength tunability of >50 nm, and side-mode suppression ratios of >50 dB.

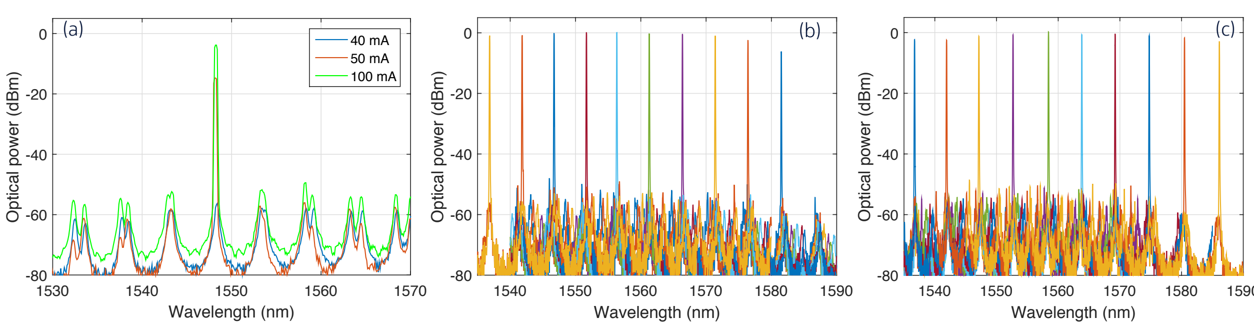

Fig. 2. Optical spectra of the packaged DRML. (a) Spectra under different SOA currents. (b) Spectra while one of the rings is thermally tuned. (c) Spectra while the other ring is thermally tuned, with the first fixed.

We demonstrate 50-Gbaud QPSK modulation by differentially driving two MIMs while the MIMs are biased at maximum reflection (or null transmission). We use a four-channel digital-to-analog converter (DAC) with a sampling rate of 120 GS/s. The differential driving voltage after RF amplifiers is about 4 V with a DC bias of 2.0 V. A pseudorandom binary sequence (PRBS) bit pattern with a length of 2^{15}–1 is used. Nyquist pulse shaping with a raised cosine frequency response with a roll-off factor of 80% is used to define the driving electrical signals for 50 Gbaud. Pre-emphasis is also applied to compensate the frequency roll-off of the MIMs. The injection current into the RSOA is kept at 150 mA. The output laser power after modulation is around -20 dBm, namely, a modulation loss of ~20 dB occurs. The modulated optical signals are received by a pre-amplified coherent receiver and the resultant waveforms are sampled by a real-time scope at 160 GS/s. Figs. 3(a) and 3 (b) give the spectrum and constellation diagram after intra-dyne coherent detection and off-line standard digital signal processing (DSP). The modulation spectrum demonstrates carrier-less modulation with Nyquist shaping. The constellation diagram of this 50-Gbaud QPSK verifies extremely low bit error ratio (BER). The measured BER is 2.2 x 10^{-5} for an optical signal-to-noise ratio (OSNR) of 31 dB. We also generate a 32-Gbaud QPSK signal with no errors in 32768 bits at an OSNR of 31 dB, shown in Fig. 3(c). These results successfully verify the coherent signal generation directly from the laser.

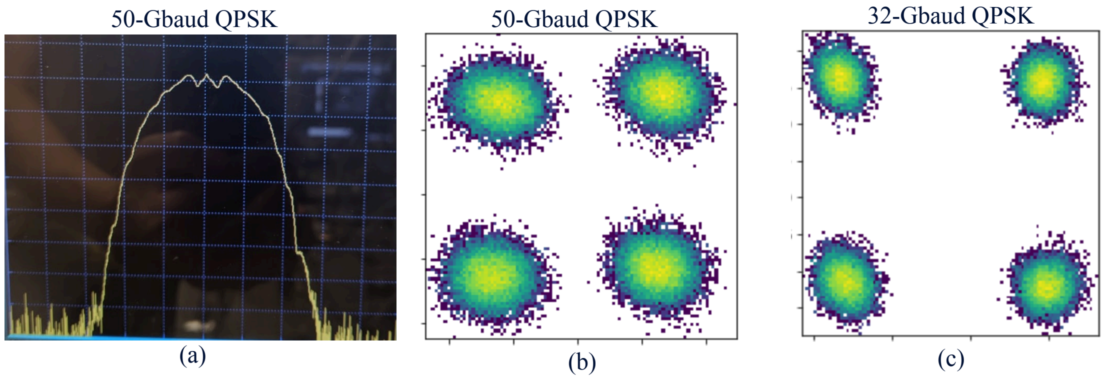

Fig. 3. (a) Spectrum for 50-Gbaud QPSK generation from DRML. (b) Constellation diagram for 50-Gbaud QPSK. (c) Constellation diagram for 32-Gbaud QPSK.

4. Conclusions

The current experimental results confirm that it is feasible to achieve IQ modulation directly from a DRML. To the best of our knowledge, this is the first demonstration of directly generating coherent optical signals from a single laser. It is also possible to have four tunable MIM-based mirrors so that dual-polarization coherent signals can be obtained. Since the DRML has the advantage of low RF power consumption from driving a very compact modulator [9-11], we expect that this device can find many applications in both short- and long-reach coherent transmission systems.

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