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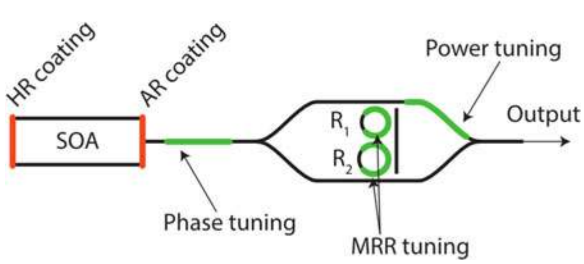

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Characterization of Hybrid InP-TriPleX Photonic Integrated Tunable Lasers Based on Silicon Nitride (Si_3N_4/SiO_2) Microring Resonators for Optical Coherent System

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Abstract: We demonstrate detailed characterization results of a hybrid InP-TriPleX photonic integrated tunable laser based on silicon nitride microring resonators. A tuning range of 50 nm across the C-band, side-mode suppression ratio (SMSR) $>$50 dB, high output power ($\sim$10 dBm), linewidth of $<$80 kHz across the whole tuning range, and μs switching speed are achieved. The delayed self-heterodyne (DSH) method is used for the linewidth measurement, the lowest linewidth can be achieve is $\sim$35 kHz. The FM noise spectrum is also measured to show the 1/f noise and white noise characterization. Furthermore, the device demonstrates performance comparable with commercial external cavity lasers in 64-QAM coherent system.

Index Terms: Silicon photonics, tunable lasers, micro ring resonator.

1. Introduction

Tunable semiconductor lasers, which can provide wide wavelength tuning range, high side-mode suppression ratio (SMSR), high output power, narrow linewidth and fast switching speeds are highly desirable for dense wavelength division multiplexing (DWDM) systems in current core networks and potentially in future optical access networks [1]. In DWDM networks, the use of coherent detection technology combined with advanced modulation formats is being employed to achieve higher spectral efficiencies to overcome the capacity limitations of current network implementations. While quadrature phase shift keying (QPSK) is now widely used in commercial optical networks, the use of more advanced modulation formats and constellation diagrams to increase the spectral efficiency are being investigated. Recent work has presented 256-QAM and 1024-QAM optical systems for

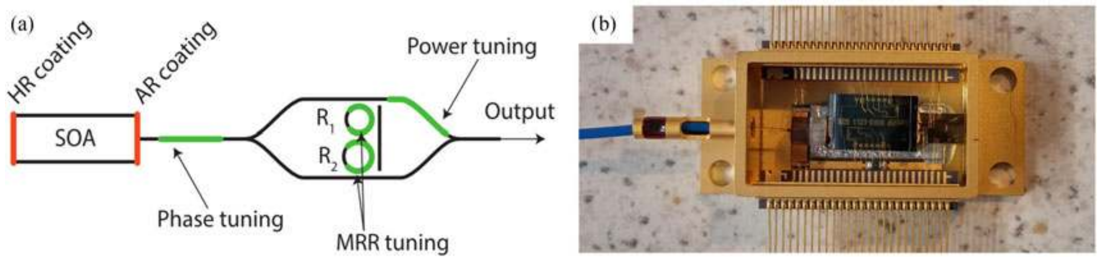

Fig. 1. (a) Schematic diagram of a MRR-ECL [7]. The thermal tuning elements in the external cavity are shown in green color. (b) Photograph of fiber pigtailed hybrid tunable laser in a butterfly package containing a TEC and NTC for thermal control of the narrow linewidth laser cavity.

access and core network applications [2], however, as the modulation format is increased the laser linewidth requirements become extremely stringent [3]. Among various types of tunable lasers, the external cavity lasers (ECL) can exhibit narrow linewidth due to their long cavity length and indeed recent work [4] has demonstrated an ECL with linewidths below 10 kHz that are suitable for higher order modulation in coherent optical systems. Due to the complexity and footprint of the ECL's, distributed feedback (DFB) laser arrays and distributed Bragg reflector (DBR) type lasers are the preferred tunable laser options for commercial coherent transceivers employing QPSK transmission. However, the linewidth of these devices is typically several hundred kHz [5] which limits their use with higher order modulation formats. A new structure of micro ring resonator external cavity laser (MRR-ECL) has recently been developed based on the TriPleX waveguide platform [6]–[8]. TriPleX, a Si_3N_4 based photonic waveguide platform, has very low optical waveguide losses ($<$0.1 dB/cm) and has shown its potential for application in a number of fields [9]. The range of applications can be enhanced by hybrid integration of TriPleX with different material platforms, to include increased optical functionality [10], which may make these devices suitable for future coherent transceivers in optical networking applications.

In [11], we initially characterize the tuning map, the relative intensity noise (RIN), linewidth, and switching time of the MRR-ECL based on the TriPleX waveguide platform, before demonstrating its performance in a 16-QAM coherent transmission system. In this paper, we undertake a detailed characterization of the laser linewidth across the whole tuning range by using the delayed self-heterodyne (DSH) method. The results show that the device has a lowest linewidth of $\sim$35 kHz and linewidth less than 80 kHz over the whole tuning range. We also demonstrate the switching time of laser when it is switched between two adjacent modes and non-adjacent modes, and under 100 and 250 microseconds tuning time are achieved, respectively. Finally, we apply the device in a coherent 64-QAM transmission system as the laser source, and achieve similar performance to a commercial ECL in a coherent 64-QAM transmission system.

2. Device Description

The structure of the device is schematically shown in Fig. 1(a). The pigtailed hybrid laser assembly has two optimized optical interfaces: the InP coupled to the TriPleX photonic integrated circuit (PIC), forming the hybrid tunable laser cavity; and the TriPleX PIC coupled to the polarisation maintaining (PM) fiber output. The InP based semiconductor optical amplifier (SOA) has a high reflective (HR) coated back-facet to reduce cavity losses, and a low reflectivity front facet to impose lasing on the external TriPleX cavity. The TriPleX waveguide circuit consists of two cascaded MRRs with slightly different radii, exploiting the Vernier effect to achieve wavelength tuning. The radii as well as the power coupling coefficients of the MRRs are chosen such that the free spectral range (FSR) of the mirror exceeds the 3 dB gain bandwidth of the SOA thereby suppressing the spectral side peaks of the mirror response to avoid lasing at undesired side modes. The result is a highly frequency selective feedback mirror enforcing single-frequency operation. The low propagation loss of the TriPleX waveguides allows for high quality resonators, resulting in several cm's of effective optical

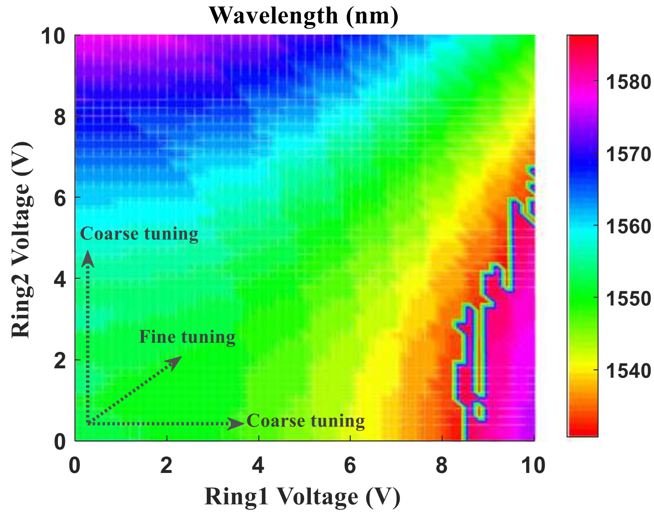

Fig. 2. Wavelength tuning map.

path length inside the cavity. In addition, by optimized on-chip spot-size convertors [9], very efficient coupling to a range of mode fields ranging from standard SM fiber (10 microns) to the modes of the InP gain section (3 microns) is achieved, resulting in low loss chip-to-chip coupling (<1 dB) between the InP and the TriPleX. The resulting laser cavity has a large cavity photon lifetime enabling narrow spectral linewidth performance compared to typical DFB/DBR lasers. The phase section of the device can be used to tune the longitudinal mode to achieve fine tuning of the wavelengths, and the output power can be optimized by using the power tuning section. The device is subsequently packaged in a fiber pigtailed butterfly package (as shown in Fig. 1(b)) containing a thermistor and thermoelectric cooler (TEC) for accurate thermal control of the device. The footprint of the MRR-ECL is comparable to conventional DFB and DBR lasers, but is smaller than conventional ECL. More details of the device including details on the radii of the rings and individual FSR can be found in [7], [9].

3. Laser Characterization

The packaged MRR-ECL was mounted on a circuit board and the temperature was set at room temperature (23 °C) using the laser diode thermoelectric cooler (TEC). The threshold current of the device was measured to be around 13 mA. Fig. 2 and Fig. 3 show the tuning map and side mode suppression ratio of the MRR-ECL as a function of the voltage applied at the two ring resonators. The current on the SOA was kept at 70 mA throughout the measurements in Fig. 2 and Fig. 3. Coarse tuning can be achieved by adjusting the voltage to either of the rings independently and more precise wavelength tuning can be achieved by using both rings together. The device has a tuning range of more than 50 nm with a SMSR in excess of 50 dB across all wavelengths. High output power (~10 dBm) can be attained by increasing the current into the SOA to greater than 200 mA, and using the power tuning section to optimize output power. Fig. 4 shows the superimposed spectra of the laser covering the whole C-band from 1530 nm to 1580 nm with an output power of ~10 dBm on each wavelength achieved with 200 mA current applied to the SOA.

The relative intensity noise (RIN) was measured to be less −130 dB/Hz at 70 mA current to the SOA as shown in Fig. 5 by using a basic RIN-measurement setup. The output of the laser was passed through an isolator and sent into a high speed photodetector. A bias-tee was used to separate the DC and AC signal from the photodetector. The DC signal was measured to estimate the shot noise of the photodetector, and the AC signal was amplified and characterized by using an electrical spectrum analyzer. In order to characterize the phase noise of the laser, the delayed self-heterodyne method was used. The diagram of the measurement setup is shown in Fig. 6. The

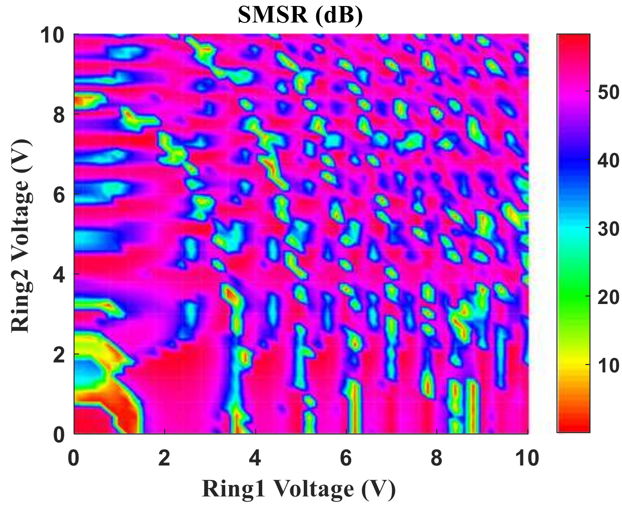

Fig. 3. Side mode suppression ratio (SMSR) of MRR-ECL versus voltage on the rings.

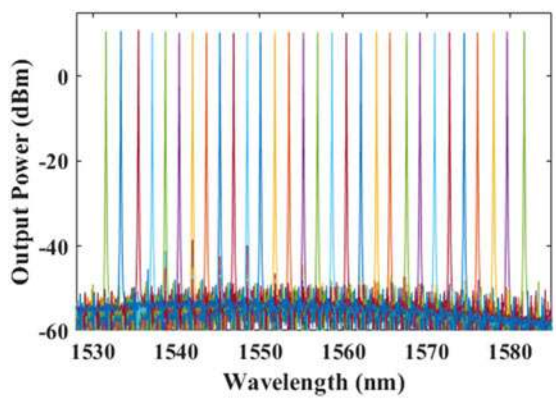

Fig. 4. Superimposed laser spectra.

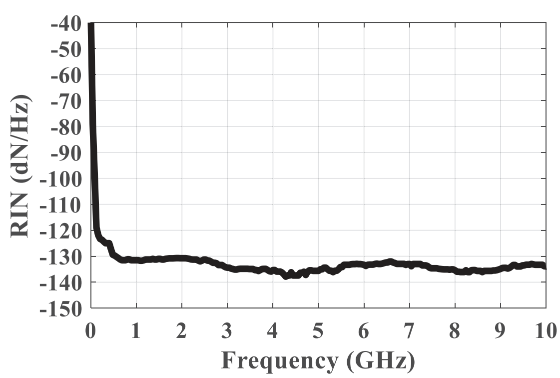

Fig. 5. RIN measurement.

laser output was firstly divided into two parts, with one part of the light passed through a 12 km single mode fiber to introduce a sufficient time delay to decorrelate the signals in the two arms, while the other part was modulated by an optical phase modulator with a 2 GHz RF signal. A 10 GHz photodiode was used to detect the signal after the two optical signals were recombined by an optical coupler. Then the linewidth spectrum can be observed by using an electrical spectrum analyzer. To

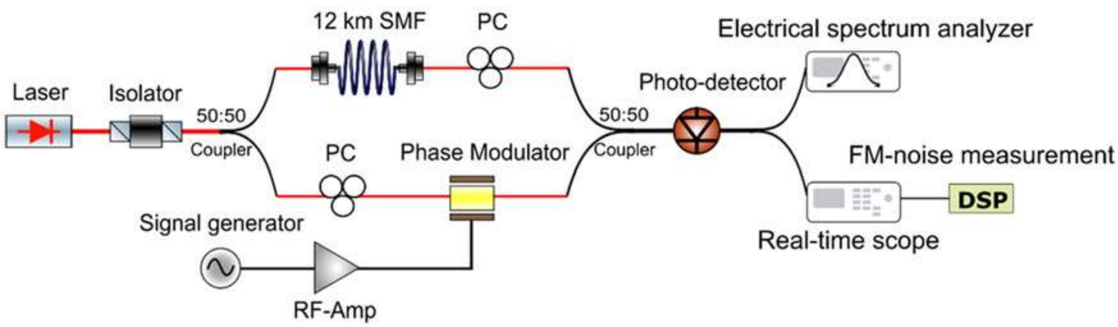

Fig. 6. Delayed Self-Heterodyne (DSH) Linewidth and FM-noise measurement setup.

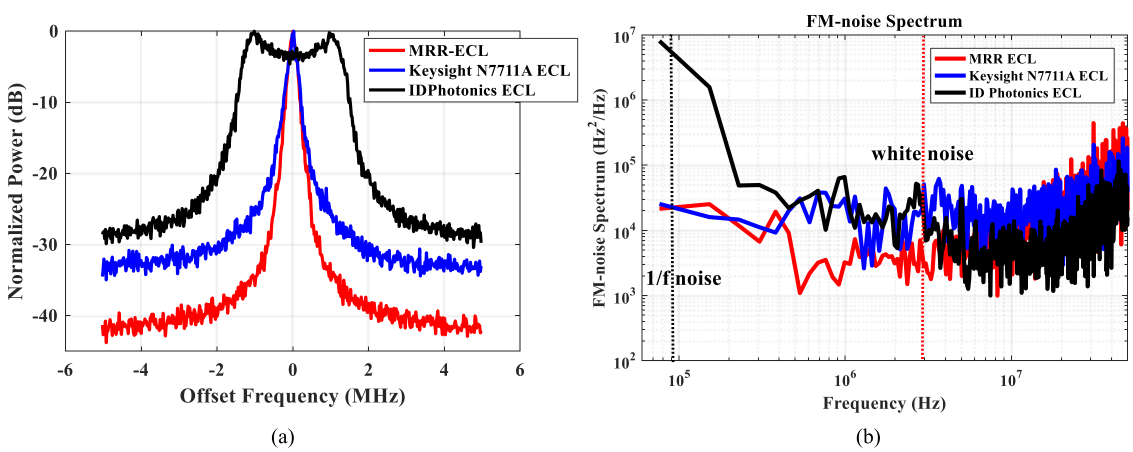

Fig. 7. (a) Linewidth and (b) FM-noise measurement.

characterize the FM-noise of the laser, a real-time scope operating at 10 GSa/s sampling rate was used to capture 400 K data samples from the detected signal for off-line digital signal processing (DSP). By analyzing the data using the technique in [12], we can recover the full information of the laser phase noise and obtain the FM-noise spectrum.

The linewidth and FM-noise spectrum of the MRR-ECL were characterized and compared with two different ECLs (Keysight N771AA ECL and ID Photonics PS-TNL). As presented in Fig. 7(a) the full spectral width of the MRR-ECL at 20 dB down from the peak is around 800 kHz, which corresponds to a laser linewidth of 40 kHz at an injection current of 70 mA to the SOA and no voltage applied to the ring resonators. For clarity we note that the linewidths measured with the DSH technique include contributions from the white noise and 1/f noise of the lasers characterised. It is clear from Fig. 7(b) that the MRR-ECL has the lowest white noise (corresponding to an intrinsic linewidth of less than 10 kHz) among the three types of lasers and a low frequency phase noise (1/f noise) that is lower than the ID Photonics ECL and compares well with the Keysight ECL. The large 1/f noise from the ID Photonics source results in the DSH result presented in Fig. 7(a) due to frequency drift of the laser on a timeframe similar to the time delay in the long arm of the DSH measurement set-up.

Fig. 8(a) shows the linewidth of the MRR-ECL measured using the DSH technique, as a function of wavelength, with linewidth under 80 kHz over the whole tuning range. The lowest linewidth can be achieved is around 35 kHz, with slightly larger linewidths observed when the laser was operated at higher wavelengths. The linewidth of the tunable laser as a function of biasing current on the SOA, with no voltage applied on the other sections is shown in Fig. 8(b). The laser shows best linewidth performance with a biasing current of 80 mA.

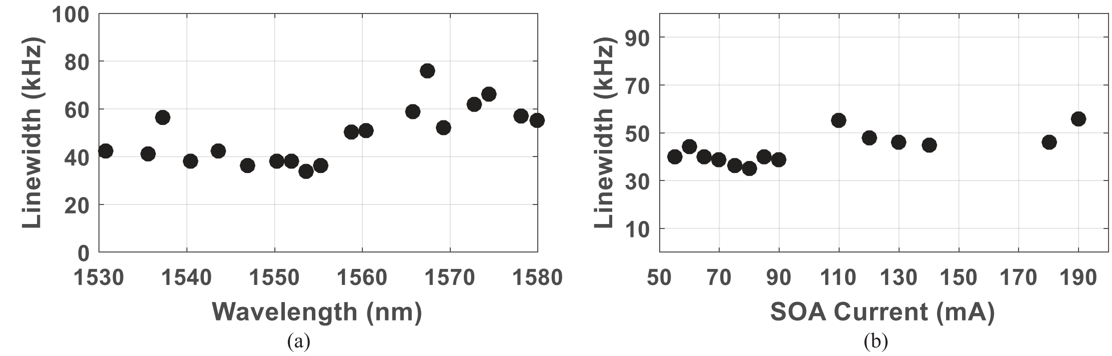

Fig. 8. Measured linewidth as a function of (a) wavelength and (b) SOA injected current.

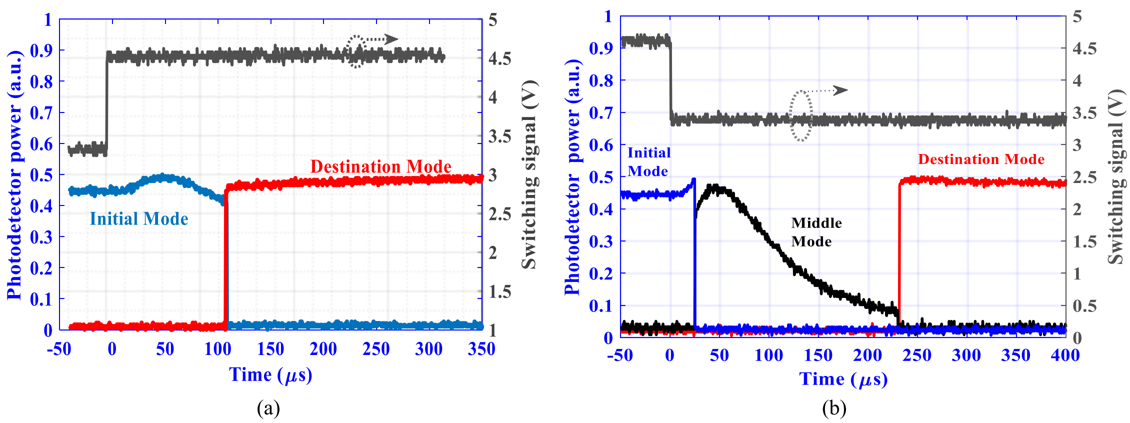

Fig. 9. (a) Laser switching times between two adjacent modes (b) two non-adjacent modes.

Finally, the tuning time of the laser was measured by applying a 100 Hz clock signal to one ring section to switch the laser between two adjacent modes and then non-adjacent modes, filtering out each mode with a 0.2 nm bandwidth optical bandpass filter, and then measuring the detected power in each wavelength as a function of time with a 10 GHz photodetector and a real time scope. In Fig. 9(a), the amplitude of the switching signal was switched from 3.3 V to 4.5 V to tune the laser wavelength from initial mode (1553.51 nm) to destination mode (1555.23 nm). Fig. 9(a) shows the received power on the initial wavelength and wavelength the laser is switched to, indicating it takes about 100 microseconds after the clock edge for the thermal tuning of the ring to induce the wavelength switch [13], but the actual switch between wavelengths occur on a sub microsecond time scale. Fig. 9(b) shows the result when switching between two non-adjacent modes by switching the signal amplitude from 4.6 V to 3.4 V. In this scenario the laser initially switches to a mode between the initial mode (1556.94 nm) and destination mode (1553.51 nm) of the switch, and it takes ∼250 microseconds after the applied electrical switching signal for the laser to reach the destination wavelength.

4. Transmission Experiment

In order to evaluate the performance of the MRR-ECL, the laser was utilized in a coherent transmission system as the signal source. In our previous work [11] we demonstrated that the MRR-ECL could be successfully employed in a 16-QAM system operating at 12.5 Gbaud. In this work, in order to further highlight the excellent linewidth and low phase noise properties of the device, we increase the order of the modulation format to 64-QAM and reduce the baud rate to 5 Gbaud. Fig. 10 shows the experimental setup we used for the 5 Gbaud 64-QAM coherent transmission. For the coherent

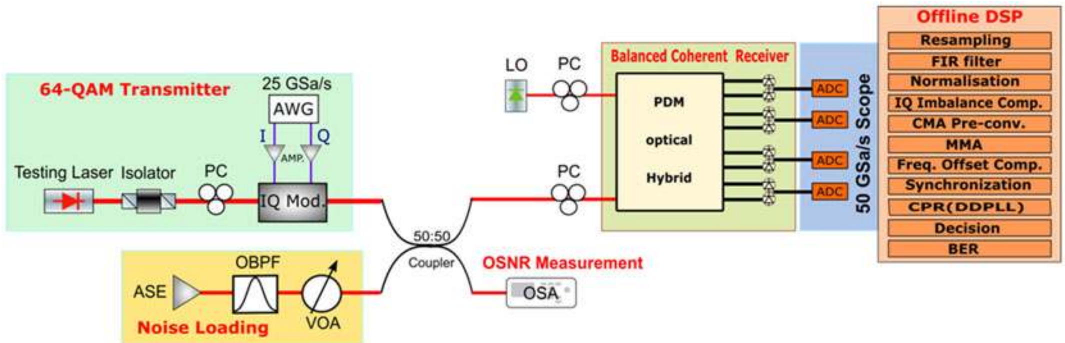

Fig. 10. Schematic of the experimental setup for 64-QAM coherent transmission.

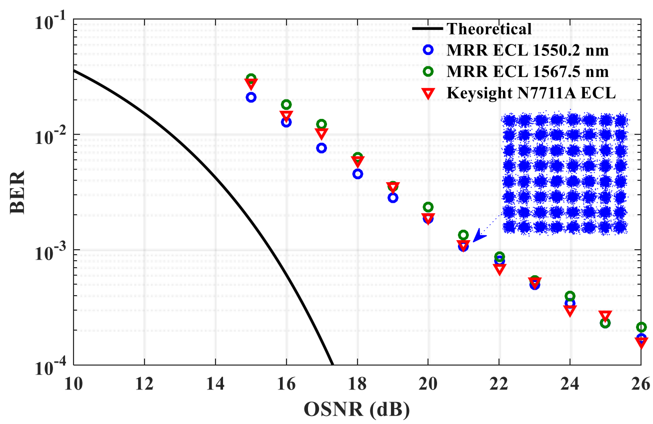

Fig. 11. OSNR versus BER curve for 64-QAM at 5 Gbaud.

64-QAM experiment, two wavelengths (1550.2 nm 1567.5 nm) of the MRR-ECL (with slight different linewidths) were used in the experiment. A commercial ECL (Keysight N7711A) was also used in the transmission experiments in order to compare with the performance of the MRR-ECL. The optical I-Q modulator was driven by two electrical signals generated from an arbitrary waveform generator (AWG) which operated at 25 GSa/s, with data streams consisting of two uncorrelated pseudo-random bit sequences (PRBS) of $2^{15} - 1$ bits periodicity. The modulated optical signal was then passed through a 3 dB splitter with one arm sent to the OSA for measuring the OSNR, and the other passed into the coherent optical receiver and captured by a real-time oscilloscope sampling at 50 GSa/s. The optical signal to noise ratio (OSNR) was changed by adding amplified spontaneous emission (ASE) from an Erbium-doped fiber amplifier (EDFA) that is passed through a 2 nm bandwidth tunable optical bandpass filter. The received signal power at the input of the coherent receiver was maintained at -19 dBm. The local oscillator (LO) used in the setup was a commercial ECL laser with a typical linewidth of $\sim$50 kHz. The required DSP functionality was performed offline. The data was first resampled to 2 samples per symbol using a priori knowledge of the clock frequency. Then the constant modulus algorithm (CMA) combined with multi-modulus algorithm (MMA) was utilized for the equalization [14]–[16]. An Mth power frequency offset compensation method is employed to compensate the frequency offset between the signal and the LO in the coherent receiver [17]. The decision-directed phase-locked loop (DD-PLL) method was employed for the carrier phase recovery, and the synchronization is achieved by adding training symbols at the beginning of the data in order to carry out the BER calculation [18].

The results for the coherent 64-QAM system at 5 Gbaud when using the MRR-ECL laser at two operating wavelengths, and the commercial laser, are presented in Fig. 11. The BER is displayed as a function of received OSNR and the constellation diagram of the received 64-QAM signal when using MRR-ECL at 1550.2 nm and an OSNR of 21 dB is presented in Fig. 11. It can be observed from Fig. 11 that the OSNR penalty compared with the theoretical curve at a BER of 10^{-3} is about 5.5 dB. As shown in Fig. 10, the performance of the MRR-ECL in terms of BER versus OSNR in the case of coherent 64-QAM systems operating at 5 Gbaud was verified to be comparable to a commercial ECL laser. As we tune the MRR-ECL from 1550.2 nm to 1567.5 nm we note a small penalty in the BER performance ($\sim$0.5 dB at a BER of 10^{-3}) due to the slightly increased linewidth at this wavelength. Nevertheless, these results indicate the excellent performance of the presented MRR-ECL in a coherent optical communication system with higher order modulation formats.

5. Conclusion

In this paper, detailed characterization of a hybrid InP-TriPleX integrated tunable laser based on silicon nitride micro ring resonators has been presented. We study the performance of the presented laser in the coherent transmission system for 5 Gbaud 64-QAM signals, and the presented laser exhibits comparable performance with a commercial ECL laser. A tuning range of around 50 nm with high output power ($\sim$10 dBm), high SMSR ($>$50 dB), and narrow linewidth of under 80 kHz across the whole tuning range makes this a promising device for use in coherent communication systems employing higher order modulation formats; especially given the ease of integration of the PIC. Furthermore, the μs switching speed indicates its suitability for use in coherent systems employing burst mode operation.

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