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Abstract—**A silicon micro-ring resonator is used to enhance the modulation speed of a 10-Gbit/s directly modulated laser to 40 Gbit/s, demonstrating a potentially integratable transmitter design for high-speed optical interconnects.**

I. Introduction

Optical technologies are seen as a promising way to address the bandwidth, density and energy challenges of interconnects and short-range links of various length scales. For those applications, the development of compact, low-power consumption, integratable and cost-effective light sources able to operate above 10 Gbit/s is of paramount importance. The use of directly modulated lasers (DMLs), typically under the form of vertical-cavity surface-emitting lasers (VCSELs) is therefore often preferred over external modulation schemes. Even though edge-emitting DMLs [1] and VCSELs [2] capable of operating at 40 Gbit/s have been demonstrated, generating such high-speed directly-modulated signals with a quality compatible with low bit-error-ratio (BER) requirements is still challenging.

For telecommunication applications, the use of direct modulation followed by optical filtering has been suggested, initially as a way to enhance the transmission performance, by converting the adiabatic chirp of the laser to intensity modulation, thereby generating high extinction ratio (ER) signals that are furthermore tolerant to dispersion. Such chirp-managed lasers (CMLs) [3] have been demonstrated with various optical filter technologies, including fibre Bragg gratings, thin-film filters, or fiber delay interferometers. However, these solutions are not easily applicable to interconnects and short range links since such optical filters tend to be bulky and unsuitable for integration.

In this work, we propose and demonstrate the use of a silicon micro-ring resonator (MRR) to enhance the modulation speed of a commercially available 10-Gbit/s DML up to 40 Gbit/s with error-free performance. Although the proof-of-concept demonstration is performed with a 10-Gbit/s distributed feedback (DFB) DML, the scheme is directly applicable to VCSELs, where it could benefit from integration of the laser on the silicon-on-insulator platform [4]. Furthermore, it is scalable to higher bit rates and able to process multiple wavelengths simultaneously thanks to the periodic response of the MRR, thus enabling a potentially low cost, low power consumption and ultra-compact high-speed multi-wavelength transmitter compatible with active optical cables technologies.

II. Experimental setup

The experimental set-up of our proof-of-concept demonstration is shown in Fig. 1(a). A 1550 nm commercially available DFB laser diode (NEL), designed for operating at 10 Gbit/s, was directly modulated at 40 Gbit/s with a $2^{11}-1$ non return-to-zero (NRZ) pseudo-random binary sequence (PRBS) and biased at 75 mA. Such a high bias current allows the adiabatic chirp to dominate over the transient chirp. It should be noted that the bias requirements would be reduced when using a VCSEL as the directly modulated source. The modulated signal was then coupled to the MRR via a tapered fibre. The free-space coupling loss to the silicon chip was compensated by an erbium-doped fibre amplifier (EDFA), followed by a broadband band-pass filter (BPF) for noise reduction. This amplification requirement would obviously be waived with hybrid integration of the VCSEL with the silicon-on-insulator chip. At the output of the through port of the MRR, the light collected with another tapered fibre was connected to the receiver. The MRRs used in this work were fabricated on a silicon-on-insulator platform by electron-beam lithography followed by reactive ion etching according to the process described in details in [5].
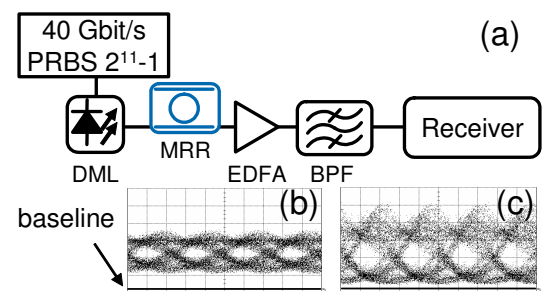

Fig. 1. Proof-of-concept experimental setup (a). Eye diagrams at the output of the DML (b) and after the MRR (c) at 40 Gbit/s.

III. Results and discussions

First, an MRR with 200 GHz FSR and a Q factor of 3300 was used. The DML was thermally tuned to the short wavelength side of an MRR resonance, as shown in Fig. 2(a). Fig. 2(b) shows the BER performance of the 40 Gbit/s directly modulated (back-to-back) and the filtered signal. By using the MRR, the BER of the signal was improved from not error-free (7.4×10^{-6}) to error-free (10^{-10}) at -15 dBm received

power. The sensitivity at 10^{-9} of the filtered signal was about -17.2 dBm. The eye diagram was significantly opened thanks to the MRR and the "0" level was largely suppressed, at the expense of some overshoot on the "1" level, as can be seen in Fig. 1(b) and (c).
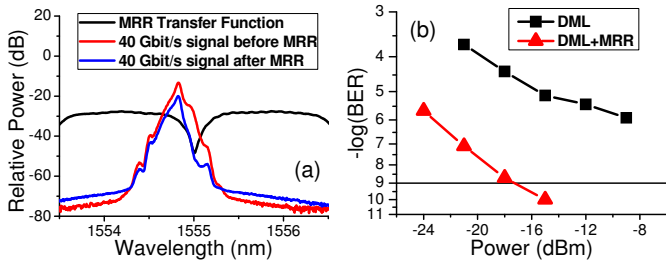

Fig. 2. Experimental results: (a) Signal spectra before and after the MRR. (b) BER performance at the DML output and after the MRR.

In order to highlight the operation principle of the proposed scheme, the MRR enhancement of the signal was simulated numerically using parameters extracted from the real 10 Gbit/s laser and MRRs with different FSR and power coupling coefficient to the ring. The 42.8 Gbit/s signal generated by the laser had a 2 dB ER and 8 GHz adiabatic chirp. The detuning tolerance between the laser and the MRR was evaluated based on the ER of the generated signal. The detuning is defined here as $\Delta\lambda = \lambda_{\text{laser}} - \lambda_{\text{resonance}}$.
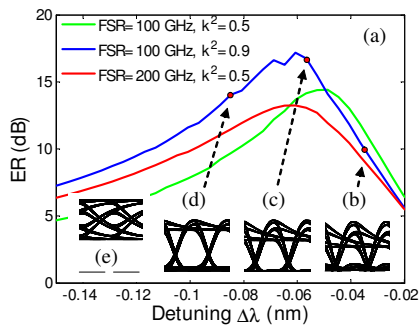

Fig. 3. Simulation results: Extinction ratio after the MRR vs detuning for different MRR designs (a). Eye diagrams of the signal filtered with a 100 GHz FSR MRR with $k^2 = 0.9$ and detunings of -35 pm (b), -55 pm (c) and -95 pm (d). The eye diagram directly at the output of the laser is also represented in (e).

Tuning the MRR resonance to the long-wavelength side of the DML spectrum is shown to result in ER improvement at the expense of some overshoot on the "1" level, as shown in Fig. 3. An optimized detuning (Fig. 3(c)) results in a maximum ER with good "0" level suppression and acceptable "1" level overshoot.

The detuning tolerance has also been experimentally assessed with 3 different MRR designs (the 200 GHz FSR MRR used in Fig. 2, referred to as 200 GHz MRR1, another 200 GHz MRR with Q factor of 3900, referred to as 200 GHz MRR2, and a 100 GHz FSR MRR with Q factor of 6800), as shown in Fig. 4(a). Since the DML performance is

slightly wavelength dependent, the BER improvement, defined as $(\log(\text{BER}_{\text{B2B}}) - \log(\text{BER}))$, was measured at a fixed received power of -15 dBm. The BER performance shows that optimum filtering by the 200 GHz MRR1 occurs at about -0.17 nm detuning, where the MRR filters out the adiabatic chirp of bits "0", as shown in Fig. 4(c). Similar to what was observed in the simulations, when tuning the laser closer to the resonance, the "0" level was further suppressed, as shown in Fig. 4(b), but the filtered signal had a larger overshoot and the BER performance degraded rapidly. When the DML signal was detuned away from the dip, the signal just went through the MRR with weaker chirp suppression and the eye diagram did not show any improvement (Fig. 4(d)). In total, the detuning range resulting in BER improvement is about 0.6 nm. The optimum detuning values observed for the other two MRRs were consistent with the 200 GHz MRR1 at ~ -0.2 nm, corresponding to 25 GHz.
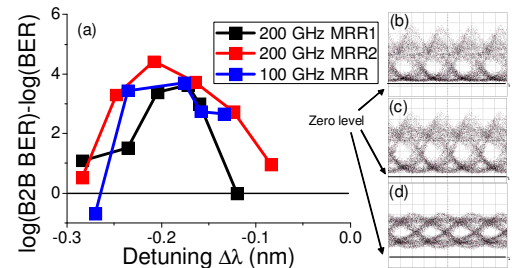

Fig. 4. Measured detuning tolerance using 3 different MRR designs (a). Eye diagrams after the 200 GHz MRR1 with detunings of -0.1 nm (b), -0.17 nm (c) and -0.3 nm (d).

IV. Conclusion

We have proposed and demonstrated the use of a silicon MRR to enhance the modulation speed of DMLs. The scheme was successfully demonstrated at 40 Gbit/s using a standard 10 Gbit/s DFB laser diode, and could be straightforwardly adapted to VCSEL sources for interconnect applications. The proposed scheme is compact and compatible with hybrid integration on the silicon platform.

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