High-Speed Direct-Modulation of InP Microdisk Lasers

J. Hofrichter[1], O.Raz[2], S. Keyvaninia[3], T. de Vries[2], H.J.S Dorren[2], T. Morf[1], B.J. Offrein[1]

[1] IBM Research – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland, jho@zurich.ibm.com
[2] Eindhoven University of Technology, Den Dolech 2, 5600MB, Eindhoven, The Netherlands
[3] Photonics Research Group, Gent University/IMEC, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

Abstract *We demonstrate for the first time high-speed direct-modulation of InP microdisk lasers by exploiting longitudinal mode competition. High-speed operation is demonstrated by means of S_{21} and PRBS modulation. We show open eye diagrams and bit-error rates up to 10 Gb/s.*

Introduction

Silicon photonics is a versatile technology platform offering unprecedented cost-advantages for optics compared to other photonic integration approaches. Silicon's transparency at 1.3 µm and 1.55 µm makes this material very attractive as waveguide material. However, based on its indirect band-gap, silicon is a poor light emitter requiring the integration of other materials with silicon for efficient on-chip laser sources, of which III-V based materials are most compelling[1]. Various approaches were presented, in which III-V material was heterogeneously integrated on top of a silicon waveguide to form electrically pumped lasers. Fabry-Perot lasers[2], DFB lasers[3], microdisk lasers[4] and microring lasers[5] were presented recently.

Remarkably, direct modulation of these lasers has attracted limited interest, presumably as telecommunication was regarded as their main application, where a narrow spectrum is required because of fiber dispersion. In data communication this requirement is less stringent as the communication distances are in the order of up to a few hundred meters only. Instead, the link power budget is more critical, limited by the insertion losses of the electro-optic modulators. Therefore, direct modulation is particularly attractive for short-reach applications. Although the static characteristics of InP microdisk lasers (MDLs) were investigated as on-chip laser sources for silicon photonics[4], their direct modulation at high speed remained to be demonstrated.

In this paper, we report on the direct modulation properties of MDL integrated with a silicon waveguide. The laser has a threshold current of 0.6 mA and exhibits a side-mode suppression ratio larger than 25 dB. By exploiting longitudinal mode competition, we are able to demonstrate a small-signal bandwidth larger than 10 GHz and demonstrate open eyes in combination with low bit-error rates at a data rate of 10 Gb/s.
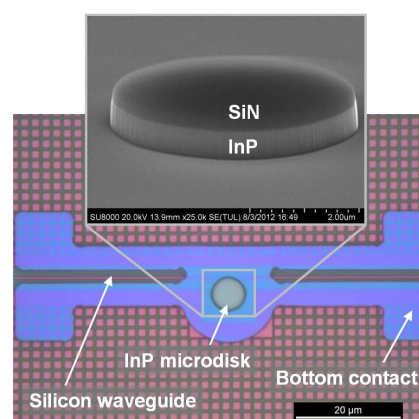
Fig. 1: Micrograph of the InP MDL. The inset shows a SEM image taken after ICP-RIE etching of the disk cavity.

Device structure and characteristics

The MDLs were fabricated by heterogeneous integration. First, a silicon photonic circuit was structured consisting of a waveguide and grating couplers on either end. Then, an InP die containing the epitaxial layer stack optimized for lasing around 1550 nm was bonded face-down by DVS-BCB bonding[6]. After removing the InP substrate wet-chemically, the laser device was structured. Fig. 1 shows the device at an intermediate step of the fabrication before applying the silicon dioxide cladding, via opening and metallization of the pads. The laser device consists of a highly n-doped bottom contact with a thickness of ~75 nm and a 500 nm-thick disk cavity as shown in the inset in Fig. 1. The diameter of the devices was 7.5 µm resulting in an active area of less than 50 µm². By electrically pumping the MDL it emits into the silicon waveguide underneath through evanescent coupling. The emission can then be coupled out of the chip into cleaved standard single-mode fibers by using the grating couplers located on either end of the silicon waveguide. Fig. 2a shows the fiber-coupled output power and the bias voltage in relation to the applied electrical pumping current. The device has a threshold current of 0.6 mA at 16 ºC and emits
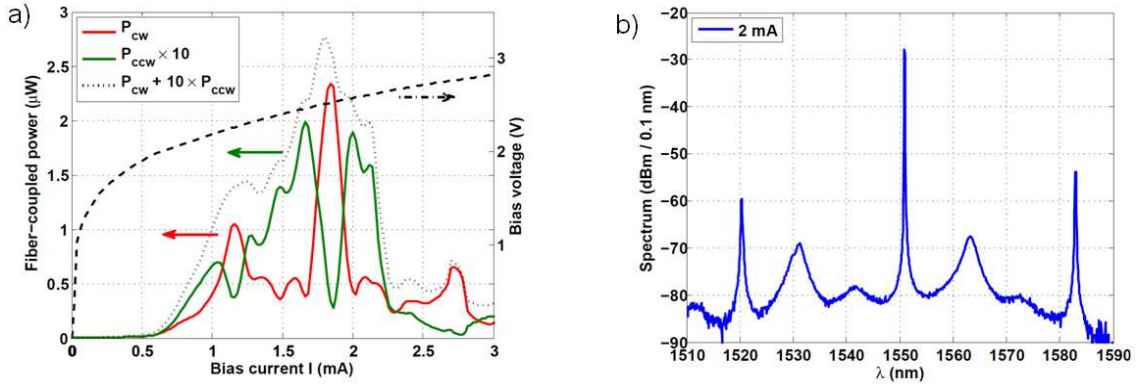
Fig. 2: Lasing operation of an MDL with a diameter of 7.5 µm: a) Fiber-coupled optical output power and bias voltage in relation to electrical bias current at 16 ºC. b) Lasing spectrum at 2.0 mA bias current.

up to 2.3 µW fiber-coupled output power into the clockwise (CW) rotating lasing mode at 1.86 mA bias current. As the grating couplers have a coupling loss of about 6 dB around 1550 nm, this power level corresponds to 9.2 µW optical power in the silicon waveguide. The counter-clockwise (CCW) lasing mode exhibits less output power because of a defect on the grating and is therefore magnified by a factor of 10 in Fig. 2a. Moreover, both counter-propagating modes are subject to mode competition and thus cross-gain suppress each other. This is evident for example at 1.86 mA, where the power of the CW mode has a local maximum and the CCW mode has a local minimum but is not fully suppressed thus inducing substantial noise by mode competition. For bias currents lower than 3.5 mA the bias voltage is lower than 3 V, thus demonstrating single-digit mW power consumption under static conditions.

Fig. 2b shows the lasing spectrum of the CW mode of the laser when biased at 2.0 mA. The central lasing mode is located at 1551 nm and exhibits a side-mode suppression ratio (SMSR) of 26 dB with respect to the higher order longitudinal lasing modes at 1520 nm and 1583 nm. The other peaks in the spectrum at around 1532 nm and 1563 nm are higher order modes with a reduced quality factor and thus low lasing power. Although Fig. 2a suggests that the optical output power is reduced for bias currents larger than 2.25 mA, in fact the higher-order longitudinal lasing mode at 1583 nm becomes dominant. As the grating couplers have a much reduced coupling efficiency at 1583 nm, the fiber-coupled output power as shown in Fig. 2a appears to be reduced.

Small-signal analysis

A small-signal analysis was carried out to investigate the frequency response of the system to small high-frequency oscillations of the bias current around a given bias point. For the given device this analysis was performed at a bias current of 1.86 mA, where the laser emits the largest fiber-coupled optical output power. The transmission parameter S_{21} was measured to evaluate the speed limitations of the device. A 3 dB-bandwidth of 11.7 GHz was determined as shown in Fig. 3, which also holds a reference measurement performed with a 40 Gb/s lithium niobate modulator. This bandwidth indicates the capability of the device to operate up to data rates of 10 Gb/s and beyond. Yet, the small signal analysis only gives an indication about the large-signal modulation properties of the device.

High-speed modulation

Large-signal experiments were performed in order to verify the actual direct-modulation properties of the laser. The laser was biased at 1.86 mA and a voltage swing of $V_{pp} = 0.2$ V was applied using a bias-tee thus switching the lasing mode at 1551 nm to the higher-order longitudinal lasing mode at 1583 nm and back. This mode competition process does not influence the internal carrier density of the device and is thus very fast and results in a large extinction ratio as we will show below. The laser emission was coupled out of the chip using
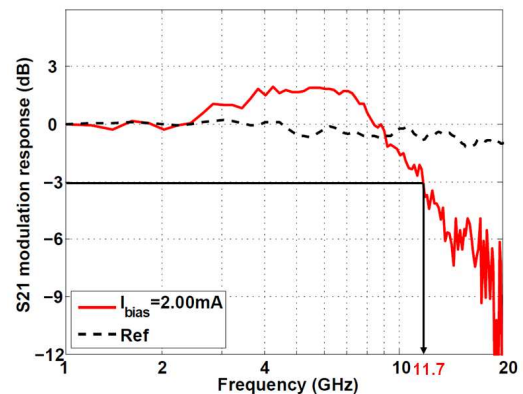
Fig. 3: Small-signal transmission bandwidth S_{21} of the InP MDL biased at 2.0 mA.
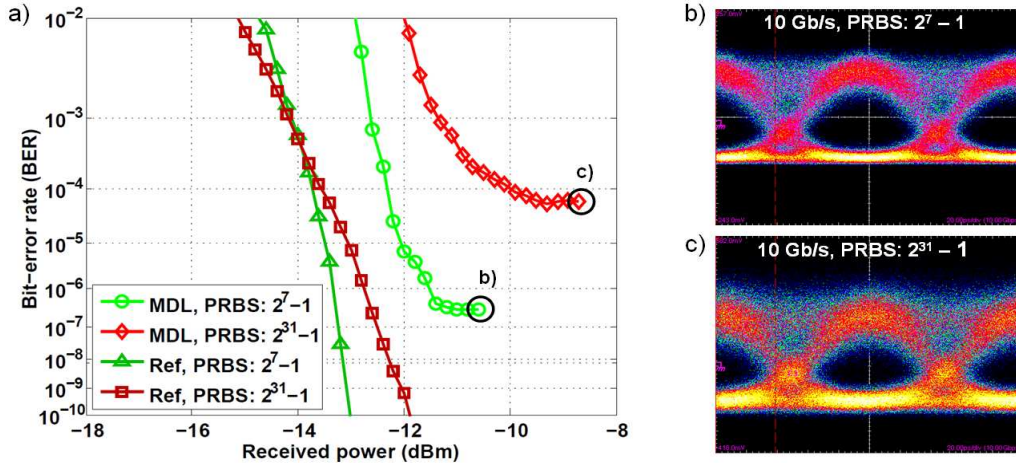
Fig. 4: Large-signal direct-modulation properties of an InP MDL: a) Bit-error rate measurement results for a data rate of 10 Gb/s and NRZ-PRBS lengths of 2^7-1 and $2^{31}-1$. b) and c) Eye diagrams for operation at 10 Gb/s and a NRZ-PRBS length of 2^7-1 and $2^{31}-1$.

the grating couplers and was subsequently amplified using an Erbium-doped fiber amplifier. After filtering out the amplified spontaneous emission noise with a tunable filter, the optical power was recorded with a 43 Gb/s photo-receiver with integrated trans-impedance amplifier. Experiments were performed at 10 Gb/s and with both non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) lengths of 2^7-1 and $2^{31}-1$, as shown in Fig. 4a. Operation below the forward error-correction (FEC) limit of 1×10^{-3} could be demonstrated for both pattern lengths. The power penalty with respect to a commercial lithium niobate reference modulator is only 1.4 dB and 2.8 dB, respectively. The error-floor is due to intensity noise of the "1"-level of the laser and the beating of the CW and CCW mode as shown in Fig. 2a. Moreover, the residual back-reflection of the grating couplers also induces an external feedback and thus destabilizes the lasing conditions. The resulting intensity noise of the "1"-level is evident from the eye diagrams shown in Fig. 4b for a data rate of 10 Gb/s (NRZ-PBRS length: 2^7-1) and in Fig. 4c (NRZ-PRBS length: $2^{31}-1$). Although both eye diagrams are open and clearly not limited by the rise- and fall-times of the lasing mode, the eyes are slightly speckled thus causing the error-floor in the bit-error-rate measurement shown in Fig. 4a.

The undesired CW to CCW oscillations may be reduced by improving the sidewall roughness and thus scattering, by using a reflector integrated in the silicon waveguide or by specially shaped coupling elements seeding one of the lasing modes[7] to foster unidirectional operation of the laser.

Conclusion
We have successfully demonstrated high-speed direct-modulation of InP MDLs enhanced by longitudinal mode competition. Based on the modal dynamics, we have demonstrated a S_{21}-bandwidth larger than 10 GHz and open eye diagrams at 10 Gb/s. We have reported bit-error rates below the FEC limit and expect error-free operation by stabilizing the laser to support unidirectional operation. This modulation scheme, which only requires a wavelength filter in addition, opens a new perspective for directly-modulated on-chip laser sources in short-reach optical communication networks.

References
[1] G. Roelkens et al., Laser & Photon. Rev. 1-29 (2010).
[2] A.W. Fang et al., Opt. Express **14**, 9203, (2006).
[3] A.W. Fang et al., Opt. Express **16**, 4412, (2008).
[4] P. Rojo-Romeo et al., Opt. Express **14**, 3864, (2006).
[5] D. Liang et al., Opt. Express **17**, 20355, (2009).
[6] S. Keyvaninia et al., Optical Materials Express, **3**, 1 (2013).
[7] J.P. Hohimer et al., Appl. Phys. Lett. **63**, 2457, (1993).