All-optical wavelength conversion using mode switching in InP microdisc laser

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Wavelength conversion using an indium phosphide based microdisc laser (MDL) heterogeneously integrated on a silicon-on-insulator waveguide is reported. Several lasing modes are present within the disc cavity, between which wavelength conversion can be performed by mode switching and spectral filtering. For the first time, low-power wavelength up- and downconversion using one single MDL is demonstrated. Operation with a bit error rate below 10^{-9} at 2.5 Gbit/s and operation below the forward-error-correction limit of 10^{-3} at 10 Gbit/s are shown without the use of additional seeding beams.

Introduction: Silicon photonics is a promising technology platform, which is expected to deliver the ever more demanding input–output (IO) bandwidth and IO density as required in future computing and communication systems. As silicon does not exhibit electrically pumped optical gain, microdisc lasers (MDLs) are interesting candidates for on-chip laser sources emitting at around 1550 nm [1]. Fig. 1*a* shows such a laser, which is heterogeneously integrated on top of a pre-structured silicon waveguide using the polymer benzocyclobutene (DVS-BCB) as adhesive [1]. Besides being used as laser sources, these devices, in combination with an external filter, have recently been demonstrated to operate as energy-efficient all-optical wavelength converters [2, 3]. Such functionality is needed, e.g. in on-chip optical networks for routing and for contention-resolution purposes.

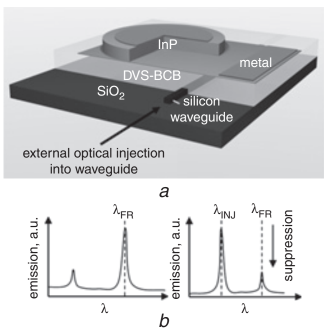

Fig. 1 *Device structure of MDL, and principle of mode switching in disc*

a Device structure of MDL heterogeneously integrated on silicon-on-insulator waveguide
InP cavity is mounted on top of pre-structured silicon nanophotonic waveguide using DVS-BCB as adhesive material and electrically connected using platinum-gold metal pads
b Principle of mode switching in disc laser
Left: free-running (FR) lasing with predominant wavelength λ_{FR}
Right: light is injected into sidemode at λ_{INJ} suppressing free-running mode at λ_{FR}

When targeting scalable systems, it is desirable to have a single integrated device exhibiting the functions of both wavelength up- and downconversion depending on the bias conditions. As we will show, MDLs can be operated in such a manner, enabling micron-size, integrated wavelength converters operating at wavelengths around 1550 nm. Their footprint and power consumption are orders of magnitude smaller than those of other wavelength conversion devices, such as silicon waveguides [4], semiconductor optical amplifiers [5], distributed feedback lasers [6], dielectric Bragg reflector lasers [7], Fabry-Pérot lasers [8] and vertical-cavity surface-emitting lasers [9]. While for MDLs it has recently been shown that wavelength conversion can be performed towards shorter wavelengths [2], no complementary conversion capabilities to shorter wavelengths were demonstrated. Also, the use of a seeding laser, which greatly improves the operation speed [3], should be avoided to lower the system complexity. In this Letter, we report on the operation of a single MDL as both an up and down wavelength converter at high bit rates. Operation with a bit error rate (BER) below 10^{-9} and with a BER below the forward-error-correction (FEC) limit is reported for a 2.5 and a 10 Gbit/s bit stream, respectively.

Mode switching by optical injection: The basic concept for employing a disc laser for wavelength conversion by mode switching can be explained using Fig. 1. Under normal operating conditions, the MDL, the diameter of which is 7.5 μm, emits light into a single longitudinal mode (Fig. 1*b*, left). Single longitudinal mode operation results from the spectral gain dependence and the large wavelength separation of ~30 nm between consecutive longitudinal modes owing to the small micron-sized cavity. Injecting light into any of the non-lasing cavity modes of the MDL forces the disc to lase at the injected wavelength. All other longitudinal modes of the MDL, including the free-running laser mode, will be suppressed (see Fig. 1*b*, right). On removing the injected light the MDL reverts to operating at its original free-running lasing mode. The device can be operated as a signal inverting wavelength converter by injecting a data signal at the suppressed lasing mode and centring a bandpass filter at the free-running mode for subsequent detection.

Static characterisation: The characterisation was performed on a custom-made setup with manually aligned fibre probes sensing the grating couplers. The threshold current of the device was ~0.25 mA and the fibre-coupled power exceeded 10 μW for bias currents larger than 3 mA. When biasing the MDL at $I_{LO} = 2.72$ mA, the mode at ~1560 nm becomes dominant. Owing to a shift of the gain spectrum and the variation of the refractive index due to Joule heating, the lasing mode at ~1590 nm becomes dominant for a higher bias current of $I_{HI} = 3.53$ mA. Static locking experiments were performed first to quantify the static extinction ratio of the lasing modes. When biasing the device with $I_{LO} = 2.72$ mA and injecting an external continuous-wave light signal at 1590 nm, an extinction of 25 dB was obtained as shown in Fig. 2 (top). For $I_{HI} = 3.53$ mA and injection at 1560 nm, an extinction ratio of over 13 dB was achieved as shown in Fig. 2 (bottom). This proves that the MDL can be injection-locked to either of its suppressed sidemodes, lending the device to wavelength conversion applications, as we will show below. The different noise floors in Fig. 2 stem from the unfiltered EDFA's amplified spontaneous emission accompanying the injected beam.

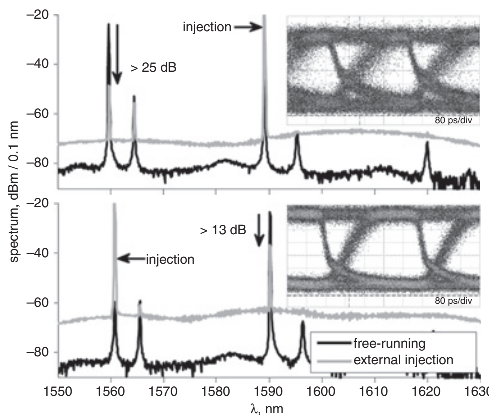

Fig. 2 *Lasing spectrum for $I_{LO} = 2.72$ mA with and without external injection at 1590 nm (top) and lasing spectrum for $I_{HI} = 3.53$ mA with and without external injection at 1560 nm (bottom)*

Insets: Dynamic operation at 2.5 Gbit/s at respective bias currents and injection wavelengths

Dynamic operation: We performed dynamic measurements to investigate the temporal behaviour of the conversion process. The sample was mounted on a thermoelectric cooler to stabilise the device temperature at 18°C. Radio-frequency probes connected the device with a current source for electrical pumping. The light was then coupled out of the chip by a grating coupler using a singlemode fibre. The spectra were then taken by an OSA. For the dynamic experiments, a tunable laser was modulated with a 10 Gbit/s lithium niobate modulator driven by a 12.5 Gbit/s pattern generator and subsequently amplified. Then, the converted light was coupled out by a circulator and amplified by a second optical fibre amplifier. The ASE of the amplifier was filtered out by a manually tunable filter centred at the wavelength of the free-running lasing mode to extract the wavelength-converted signal. Finally, the signal was detected in a high-speed photodiode and either attenuated for BER measurements using a 12.5 Gbit/s BER tester, or detected by a high-speed optical sampling scope.

First, the eye diagrams were recorded demonstrating wavelength conversion at 2.5 Gbit/s in both conversion directions, as shown in Fig. 2 (insets). Then, BER measurements were performed to quantify the quality of the wavelength converted signal for a bias current of $I_{HI} = 3.53$ mA. For 2.5 Gbit/s and a non-return-to-zero pseudorandom binary sequence (PRBS) length of $2^{31} - 1$, operation with a BER of 1×10^{-10} was achieved with a power penalty of 8 dB at an injection power level of 1.5 dBm, as shown in Fig. 3. Assuming a coupling loss of 6 dB, the corresponding emitted waveguide power is 60 μW, while the injected waveguide power is 355 μW. Although using no seeding beam greatly simplifies the operating condition, the disadvantages are an increased turn-on delay and a random turn-on behaviour as the mode has to recover from noise and spontaneous emission, which explains the large power penalties. The penalties can be improved by increasing the output power of the device and carefully trading off the extinction ratio. The inset in Fig. 3 displays the eye diagram at the minimal BER. The extinction ratio is 8.4 dB. At a speed of 10 Gbit/s and with a PRBS length of $2^7 - 1$, a BER of 3×10^{-4} could be achieved at a power penalty of 9 dB. This BER is sufficient for applications using FEC.

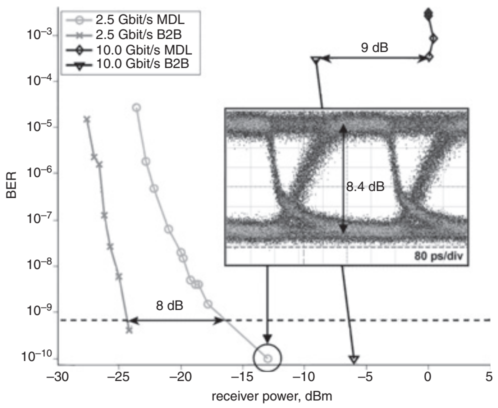

Fig. 3 *Bit error rate measurements of MDL and back-to-back (B2B) system at data rates of 2.5 and 10 Gbit/s*

MDL bias current is $I_{HI} = 3.53$ mA
Inset: Eye diagram obtained for BER of 10^{-10} at 2.5 Gbit/s

Conclusions: We have demonstrated the wavelength up- and downconversion in a single MDL heterogeneously integrated on top of an SOI waveguide. To investigate the application in the system context, the wavelength conversion experiments have been performed without seeding. For the first time, it has been shown that a single MDL can perform both up- and downconversion, enabling large-scale integrated wavelength conversion systems. Static extinction ratios of 25 and 13 dB, respectively, were shown for injection locking to a sidemode. Operation at 2.5 Gbit/s with a BER lower than 1×10^{-9} and a dynamic extinction ratio of over 8 dB are reported. Furthermore, we demonstrate operation at 10 Gbit/s with a BER lower than 1×10^{-3}, i.e. below the FEC limit. The demonstrated speed is of the order of the CPU clock speed and thus suitable for network-on-chip applications.

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