Widely Tunable O-band Laser with Narrow Linewidth, Fast Switching Speed and an Integrated SOA.

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Abstract *We present an O-band widely tunable laser capable of discrete tuning over 28 nm featuring an integrated SOA which enables optical powers up to +14 dBm. A fast switching time of 7.3 ns and linewidth of 150 kHz were recorded.*

Introduction

New digital applications such as artificial intelligence (AI), machine learning (ML) are placing strain on hyperscale datacentre networks. Today, data is delivered via pluggable optical transceivers into electronic switch ASICs. State of the art commercial switches have a capacity of 25.6Tbps while the 51.2Tbps products are being announced. Continued scaling using the traditional datacentre network architectures becomes increasingly challenging in terms of input/output (I/O) bandwidth and power consumption and new architectures are needed.

Switching in the optical domain rather than the electronic domain can contribute to overcoming these challenges and many different flavours of optical switching have been proposed and studied over many years [1-4]. Promising architectures propose optically switching a large proportion of the total traffic, and only electronically switching what is necessary [5]. Passive switching can be achieved using tunable lasers and arrayed waveguide grating routers (AWGR) offering the potential for dramatic reduction in power consumption.

A key enabling technology for these wavelength routed optical circuit switching architectures is the tunable laser. To be compatible with today's datacentre networks these lasers should operate in the O-band, with a tuning range of tens of nanometers and must have linewidth and phase noise characteristics suitable for coherent data transmission. In order to effectively handle the required workloads, switching times in the nanoseconds are required.

Lasers such as the Sampled Grating Distributed Bragg Reflector (SG-DBR) [6] can achieve tuning across a wide range of over 50 nm by means of a Vernier tuning effect. Their current-injection based tuning mechanism allows for fast optical switching at the cost of broad linewidths. Using thermally tuned SG-DBR-like lasers [7], similar tuning ranges can be achieved while attaining ultra-low linewidths. Likewise, ring-resonator based devices in the O-band have also demonstrated ultra-low linewidth using thermal tuning [8]. However the slower response time of thermal tuning limits their speed. As such, the combination of narrow linewidth and fast switching has remained elusive.

Previous work using a C-band dual ring laser [9] has demonstrated the capability of both < 450 kHz linewidth and < 4 ns switching time [10]. In this paper, we present a related set of devices however this time operating in the O-band, and with the addition of a Semiconductor Optical Amplifier (SOA) to allow for optical powers of up to +14 dBm to be achieved, an important feature for viability in coherent data networks. Some of the new designs also feature an Asymmetric Mach-Zehnder Interferometer (AMZI) to improve mode selection. To the best of our knowledge these are the first tunable lasers operating in the O-band which can achieve both nano-second tuning speed and ~100 kHz linewidth.

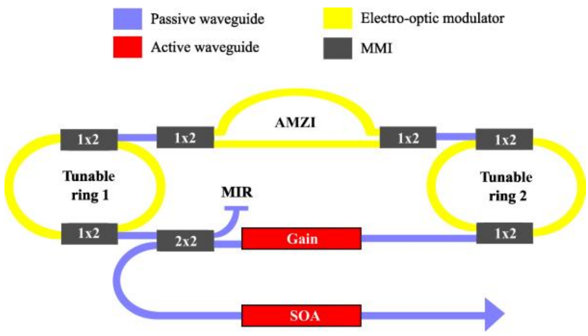

Fig. 1: Schematic of the dual-ring laser structure with an AMZI and integrated SOA.

Device design

A schematic of the dual-ring laser can be found in figure 1, which consists of 4 discrete tuning sections within a loop cavity. Optical gain is supplied from a 1000 µm long gain section, which features an InGaAsP multi-quantum well

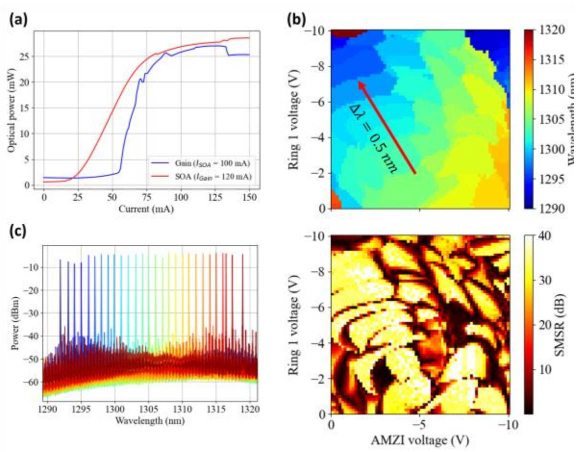

Fig. 2: Characterisation of the tunable ring laser with AMZI and SOA. (a) The LI characteristics of the gain and SOA sections. Threshold occurs near 55 mA, while the range of SOA transparency to saturation is from 20 to 75 mA. (b) Tuning maps showing peak wavelength and SMSR as a function of Ring 1 and AMZI voltages while Ring 2 is unbiased. Adjacent modes are separated by 0.5 nm. (c) Individual spectra spaced 1 nm apart over 28 nm. The gap near 1318 nm is a result of limited tuning in the AMZI.

structure, supplying optical gain near 1310 nm. Wavelength selectivity is achieved using two tunable ring-resonators which act as transmission filters, that have a Free Spectral Range (FSR) that scales with their circumference. The rings in devices discussed here are ~900 µm in circumference, producing an FSR of about 0.5 nm, with a slight pitch between the two to allow for Vernier tuning. Coupling in and out of the rings is done using Multi-Mode Interferometers (MMI) and a broadband Multi-mode Interference Reflector (MIR) is used to terminate one end of the loop, to ensure uniform propagation in one direction.

Two unique laser designs were considered here. The first is similar to that of the C-band laser from [10], where the third tuning section is a phase modulator between the two rings. The second, more novel design (pictured in figure 1) features a 1000 µm SOA section at the output of the cavity. It also replaces the phase section with an AMZI, which acts as a tertiary broadband filter. The length difference between the two AMZI arms generates a transmission spectrum with an FSR of 30 nm. Each of the rings and phase/AMZI sections are electro-optically tuned via a reverse bias voltage, which eliminates carrier injection and subsequent linewidth broadening, as well as self-heating of the chip. Additionally, it also reduces the power drawn during operation. The total footprint of the device is 3 mm^2.

Experimental setup and characterisation

The bare-die laser was characterised by mounting it on a PCB using thermally and electrically conductive epoxy. This PCB was affixed to a copper heatsink integrated with a thermo-electric cooler and thermistor to allow for a stable operating temperature of 25 °C to be maintained. The light-current (LI) response was measured using a wide-area photodiode to collect the light exiting the front facet. The LI response of both the gain section and SOA section was recorded in figure 2(c). A threshold current of about 55 mA was observed. The SOA reaches transparency at 20 mA and hits saturation at 75 mA. For all following measurements, a fixed gain current of 120 mA and SOA current of 80 mA can be assumed. The optical power at saturation exceeds 25 mW (+14 dBm), though one can assume that the on-chip power may be larger provided suitable integration.

Wavelength selectivity is achieved by varying the ring and AMZI voltages over a range of 0 to -10 V. Suitable operating points can be found by sweeping each of the 3 section voltages, to produce tuning maps as shown in figure 2(a). Peak wavelength and side-mode suppression ratio (SMSR) were recorded on a wavemeter, using a lens and collimator to couple into an optical fibre. These tuning maps demonstrate that a series of 0.5 nm spaced modes can be accessed by tuning Ring 1 to shift its transmission peaks relative to a static Ring 2. The AMZI can be used as a phase-modulator to align the cavity modes with the shifted transmission peaks. Notably, while the maximum SMSR shown on the tuning maps is limited at 40 dB, this was a limit of the wavemeter used for high-speed data capture. In fact, SMSRs of over 45 dB were recorded in certain modes. A full range of wavelength tuning can be achieved using a full characterisation space of both rings and AMZI sections. Figure 2(b) demonstrates tuning over 1292-1319 nm in discrete 1 ($\pm$0.1) nm steps, recorded on an optical spectrum analyser, by tuning the three sections together. In principle, the achievable grid spacing can be modified by varying the size of the rings. An SMSR of over 30 dB could be maintained in each of these modes. The tuning gap near 1318 nm can be attributed to the AMZI not being able to achieve a full 2π phase shift over the tuning range from 0 to -10 V.

The optical switching speed was measured using a frequency discrimination technique. This was done by passing the optical signal through a tunable grating filter and recording the transmitted power on a photodetector. By selecting two operating points inside and outside the filter bandwidth and modulating one of the rings to switch between points, the transient response can be measured in the electrical domain on an oscilloscope. Likewise, the

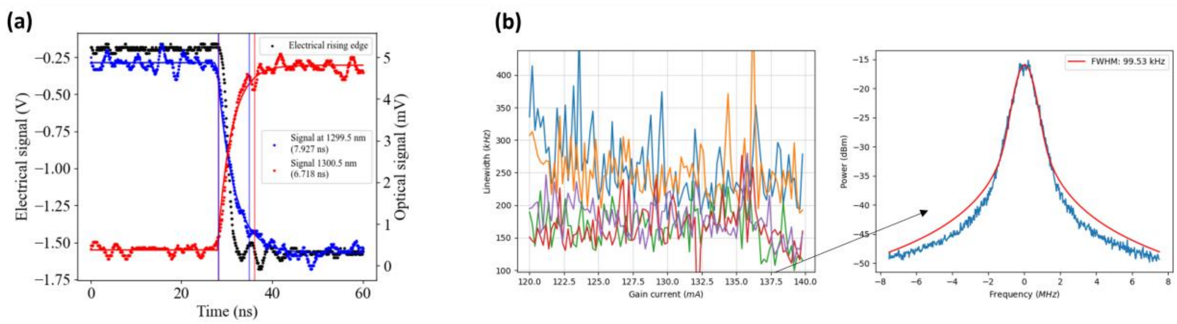

Fig. 3 a) Switching speed measured using a frequency discrimination technique. The red and blue curves show optical signals at 1299.5 nm and 1300.5 nm , having an average switching time of 7.3 ns. (b) Linewidth measured using a delayed self-heterodyne technique as a function of gain current, sampled over five separate instances. The linewidth averages between 150-250 kHz, with the lowest recorded value being 99.5 kHz.

linewidth was measured with a delayed self-heterodyne technique [11], using a 2 GHz modulation signal and 25 km fibre delay. Injection current was supplied using an ILX current controller with a low-noise filter to minimise electrical noise, and the output signal was recorded on an electrical spectrum analyser.

Results

Two operating points were selected at 1299.5 nm and 1300.5 nm, spaced only by a change in Ring 1 voltage of 1.4 V. Ring 2 was fixed at 1.9 V and the AMZI at 2 V. The tunable filter was adjusted such that only the mode at 1299.5 nm was within its bandwidth. A square wave generator could be used to supply a peak-to-peak voltage of 1.4 V at 100 kHz with a 50% duty cycle, to facilitate switching. Figure 3(a) shows both the input electrical signal and output optical signal during the transition between states. The second optical signal is the complementary signal with the filter centred at 1300.5 nm. The switching time is measured as the time taken to transition from 10% to 90% of the difference between states. The electrical switching time was measured to be 3.7 ns. The switching time of the optical signal was measured to be 7.9 ns on the falling edge of 1299.5 nm signal and 6.7 ns on the rising edge of the 1300.5 nm signal using an exponential fit, resulting in an average value of 7.3 ns. While this value is slower than the <4 ns measured previously with the C-band devices, this can be attributed to a slower electronic response of the bare-die testing compared that of a packaged device.

Linewidth was measured on the device with no SOA. The measured electrical spectrum was fitted using a Voigt function and the Lorentzian full-width half-max (FWHM) extracted as the intrinsic linewidth. The linewidth was sampled multiple times over a range of gain currents from 120 to 140 mA and all other sections unbiased. This range was selected as it ensured no mode hops from the set wavelength of 1319 nm. The average linewidth across each of the five sweeps performed lies in the range of 150-250 kHz, while the lowest recorded spectrum was found to be 99.5 kHz.

Conclusions

We demonstrate for the first time a fast-switching, low-linewidth widely tunable dual-ring laser operating in the O-band. The laser was shown to be capable of discrete tuning on a fixed 1 nm spaced grid over almost 28 nm, with other grid spacings possible by selecting suitable ring sizes. The integrated SOA section allows for optical powers of up to +14 dBm to be obtained which are required to overcome losses in network elements including optical switches and coherent modulators. The device achieves the desirable combination of a nano-second switching speed of 7.3 ns, as well as linewidth in the range of 150-250 kHz, while maintaining a small monolithic footprint. This performance makes it a promising candidate for phase sensitive applications such as coherent optical communications, including optical circuit switching, as well as non-communication applications such as FMCW LiDAR.

References

[1] W. Wang, L. G. Rau, and D. J. Blumenthal, "160 Gb/s Variable Length Packet/10 Gb/s-Label All-Optical Label Switching With Wavelength Conversion and Unicast/Multicast Operation," J. Lightwave Technol. **23**, 211- (2005)

[2] S. J. B. Yoo, "Optical Packet and Burst Switching Technologies for the Future Photonic Internet," in *Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4468-4492, Dec. 2006, doi: 10.1109/JLT.2006.886060.

[3] H. Ballani, P. Costa, I. Haller, K. Jozwik, K. Shi, B. Thomsen, and H. Williams, "Bridging the Last Mile for Optical Switching in Data Centers," in *Optical Fiber Communication Conference*, OSA Technical Digest (online) (Optica Publishing Group, 2018), paper W1C.3.

[4] Q. Cheng, M. Bahadori, M. Glick, S. Rumley, and K. Bergman, "Recent advances in optical technologies for data centers: a review," Optica **5**, 1354-1370 (2018)

[5] K. Sato, H. Matsuura, R. Konoike, K. Suzuki, K. Ikeda, and S. Namiki, "Prospects and challenges of optical switching technologies for intra data center networks," J. Opt. Commun. Netw. **14**, 903-915 (2022)

[6] M.-H. Lee, F. Soares, M. Baier., M. Möhrle, W. Rehbein, and M. Schell, “53 nm sampled grating tunable lasers from an inp generic foundry platform,” in [Semiconductor Lasers and Laser Dynamics IX], 11356, 1135605, SPIE (2020).

[7] R. R. Kumar, A H¨ansel, M. F. Brusatori., L. Nielsen, L. M. Augustin, N. Volet, and M. J. R. Heck, “A 10-kHz intrinsic linewidth coupled extended-cavity DBR laser monolithically integrated on an InP platform,”Opt. Lett. 47, 2346–2349 (May 2022).

[8] A. Malik, J. Guo, M. A. Tran, G. Kurczveil, D. Liang, and J. E. Bowers, "Widely tunable, heterogeneously integrated quantum-dot O-band lasers on silicon," Photon. Res. **8**, 1551-1557 (2020)

[9] S. Andreou, K. A. Williams and E. A. J. M. Bente, “Electro-Optic Tuning of a Monolithically Integrated Widely Tuneable InP Laser With Free-Running and Stabilized Operation,” Journal of Lightwave Technology 38, 1887–1894 (2020).

[10] G. Jain, S Andreou, C. McGuinness, M. D. Gutierrez-Pascual, M. Troncoso-Costas, L. N. Venkatasubramani, L. P. Barry, L. Augustin, F. Smyth, and S. Duggan "Widely tunable C-band laser and module with fast tuning and narrow linewidth", Proc. SPIE 12424, Integrated Optics: Devices, Materials, and Technologies XXVII, 124241M (17 March 2023); https://doi.org/10.1117/12.2668652

[11] T. N. Huynh, L. Nguyen, and L. P. Barry, ‘Delayed Self-Heterodyne Phase Noise Measurements With Coherent Phase Modulation Detection’, *IEEE Photonics Technology Letters*, vol. 24, no. 4, pp. 249–251, Feb. 2012, doi: 10.1109/LPT.2011