# Wavelength Tunable Directly Modulated Laser for TWDM Applications

Ankit Sharma(1), Aleksandra Kaszubowska-Anandarajah (2,1), Michael J Wallace (3), Gaurav Jain (3), Frank Smyth(3), Jules Braddell(3), and Prince Anandarajah(1, 2)

(1) Photonics Systems and Sensing Lab., School of Electronic Engineering, Dublin City University, Glasnevin, Dublin 9, Ireland. (ankit.sharma24@mail.dcu.ie),
(2) CONNECT Research Centre, Dunlop Oriel House, Trinity College Dublin, Dublin 2, Ireland
(3) Pilot Photonics, Invent Centre, Dublin City University, Dublin 9, Ireland

**Abstract** *A PIC transmitter for application in TWDM passive optical networks is demonstrated. The device generates four 100 GHz-spaced channels and features an integrated section for chirp control that enables error-free transmission of 10 Gb/s OOK data over 50 km of fiber.*

## Introduction

Photonic integrated circuits (PICs) have garnered a lot of interest due to their ability to offer reductions in size, weight, power, improved performance and stability over discrete solutions[1]. The biggest benefits, with the implementation of PICs in telecommunication applications, are reaped in the cost sensitive short reach networks that includes access and datacenter networks. Passive optical networks (PONs), that utilise optical fiber links to provide the end-user connectivity, have become one of the predominant access network options. The PON standards are steadily evolving due to the ever-increasing demand for bandwidth. A relatively recent advance involves the use of wavelength division multiplexing (WDM) together with the more common time division multiplexed (TDM) approach. This format is known as time and wavelength division multiplexing (TWDM)[2] and while it enables bandwidth growth, it places stringent technical demands on the optical components and makes it more challenging to meet the cost targets required in high-volume PON applications.

To date, externally modulated lasers (EMLs) have typically been required to meet the technical requirements of TWDM networks. However, EMLs are a relatively high-cost laser transmitter compared to typical PON transmitters. Furthermore, they require higher cost and higher power laser drivers. For these reasons, the industry would prefer a directly modulated laser (DML) alternative to reduce the cost and complexity of TWDM transceivers.

A key challenge with direct modulation is the frequency chirp imposed on the modulated signal. The chirped signal is more susceptible to fiber dispersion effects, which limits the transmission distance achievable by DML based transmitters. Optical injection locking (OIL), realized using a master-slave laser architecture, can be used to reduce the chirp, enhance the transmission distance[3]-[5], and increase the modulation bandwidth (MBW) of a DML[6]. However, meeting the wavelength tunability requirements of TWDM, particularly at high speed is challenging under OIL conditions. A final feature, typically required in TWDM networks is wavelength stability during burst mode transmission, with a high extinction of the light during the off periods. Many of these requirements pull in opposite directions. Direct modulation makes long distance transmission challenging. Fast wavelength switching and burst mode operation make wavelength stability challenging, and so on.

In this paper, we present for the first time a wavelength tunable directly modulated laser transmitter for TWDM networks that is specifically architected to meet these challenging and often opposing requirements. Improving on the device presented in[7] the PIC device integrates (1) a master laser for wavelength tunability and overall stability, (2) a directly modulated slave laser, (3) an OIL and chirp control mechanism offering independent control over the integrated lasers, and (4) a semiconductor optical amplifier (SOA) for burst-mode transmission and extinction control. It is based on ridge waveguide technology and offers regrowth free fabrication with potential for very low cost manufacture, a key requirement for TWDM networks.

This paper reports on the device design, its key features, and relevant characteristics for its use in TWDM networks including 10Gb/s direct modulation over 50km, on four 100GHz spaced wavelengths, and burst-mode transmission with minimal interference on other channels.

## Device design and fabrication

The device was fabricated using a standard 1550 nm material, having 5 strained $Al_{(0.24)}Ga$-$In_{(0.71)}As$ quantum wells in the active region on an n-doped In-P substrate. The total length of the PIC is ~2 mm and it consists of the four main components defined using 8 independently tuned laser sections (as shown in Fig. 1). These

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

components are the master laser (ML), variable optical attenuator (VOA), slave laser (SL), and the semiconductor optical amplifier (SOA). A 2 µm ridge waveguide couples light between the adjacent section. The front (output) and back facets are anti-reflective coated. The SL and ML are formed by introducing gain sections between two reflector sections created using high-order surface grating structures[8] defined using electron-beam lithography. A short VOA separates ML and SL. A 10 µm gap is maintained between contact pads of chips to isolate the flow of current supplied to adjacent sections. The length of the slave gain section is kept short to reduce the photon lifetime and increase the modulation bandwidth (MBW). Moreover, the bandwidth of the laser is also maximised by optimisation of the area of RF contact pad to lower the parasitic capacitance. The SOA is used to boost the output power when transmitting and dampen the power when not transmitting and has an angled waveguide to reduce reflections.

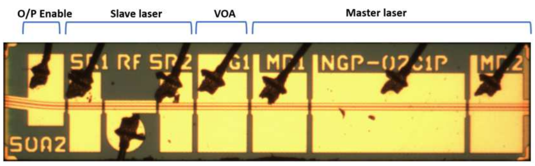


**Fig. 1:** Fabricated 8 section PIC.

### Static characterization

Initial characterization of the PIC involved obtaining optical spectra of the ML and SL lasing at distinct wavelengths (to verify that each laser operates as an independent source). We use an ultralow noise multichannel current source and thermo-electric cooler (TEC). The resultant spectrum, with ML lasing at 1531nm and SL at 1532nm is shown in Fig. 2(a).

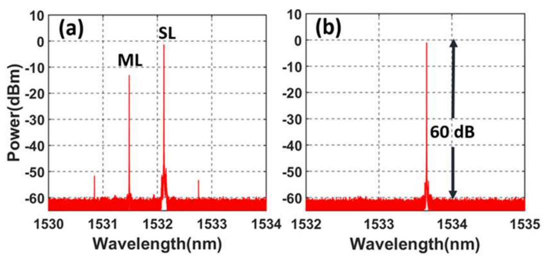


**Fig. 2:** Optical spectrum of SL and ML **(a)** lasing independently and (b) after achieving injection locking.

To obtain injection locking, ML is tuned towards SL by linearly increasing the currents in master refletor-1 (MR1), master gain (MG), and master reflector-2 (MR2) sections. The injection locked spectrum, with 60 dB SMSR, is shown in Fig. 2(b). The process of optimising the ML and SL biases was then repeated to obtain operating points for four wavelength channels on a 100 GHz grid, as shown in Fig. 3 (measured with an optical resolution of 0.16 pm).

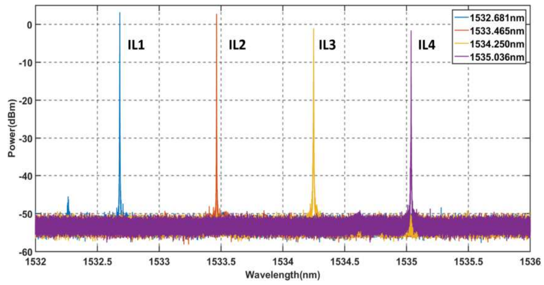


**Fig. 3:** Spectrum of four 100 GHz wavelength channels.

### Data Modulation

Having identified the required wavelength channels, we carried out a transmission test on each of the channels, using the experimental set-up shown in Fig. 4. To this effect, the RF section of the SL was directly modulated with a $2^{11}$-1 pseudorandom bit sequence (PRBS) at a data rate of 10 Gb/s and a peak-to-peak voltage of 2V. To collect the emitted light from the chip, a lens-ended fiber mounted on an auto alignment translation stage system was used. 10% of the power was fed to an optical spectrum analyser (OSA), to ensure the stable operation of the transmitter. The remaining 90% was detected using an avalanche photodiode (APD), either directly, for the back-to-back (B2B) test, or after the transmission over standard single mode fiber (SSMF). An external VOA was placed before the APD to vary the power falling on the detector.

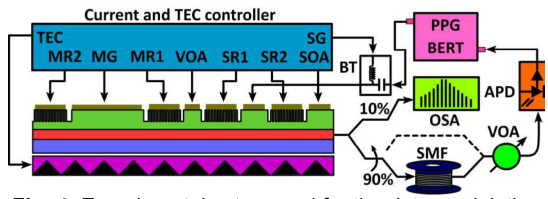


**Fig. 4:** Experimental setup used for the data modulation

To verify the impact of the OIL, we first modulated the SL while the ML was turned off and observed the eye diagram of the received signal on the oscilloscope. As can be seen in Fig. 5(a), without the OIL, the limited modulation bandwidth (MBW) of the SL corrupts the signal. However, when the ML is turned on and OIL is achieved, the MBW is enhanced and a clean and open eye is received, as seen in Fig. 5(b). Next, the injection level is varied, by adjusting the bias of the VOA section, to minimise the direct modulation induced chirp. Fig. 5(c) shows the optical spectrum of the modulated SL for various levels of optical injection. There is a reduction in spectral width of the signal when the current applied to the VOA section is increased from 1 to 4 mA, indicating a substantial decrease in the frequency chirp.

To verify the ability of the OIL to reduce the

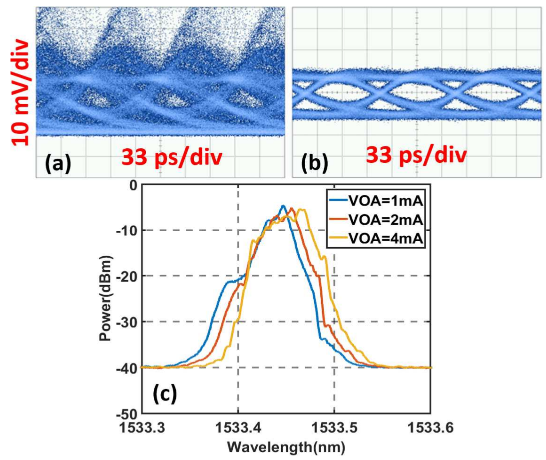


**Fig. 5:** Eye diagram of a directly modulated SL (a) without OIL, (b) after OIL, (c) spectrum of the SL for different levels of injection.

chirp and extend the transmission distance, the signal was transmitted over 25 and 50 km of SMF and the bit error rate (BER) as a function of received optical power was measured.

For the sake of clarity, the BER versus received optical power are plotted for two of the injection-locked (IL) wavelength channels (IL2=1533.46 nm and IL4=1535.03 nm) and shown in Fig.6 (a) and (b) respectively. From the plots it can be seen that, for both transmission distances a BER of 1e$^{-9}$ or better is achieved at both chirp compensated IL wavelengths. The insets in Fig. 6 show the received eye diagrams for B2B and after 50 km fiber transmission, showing a minimal degradation in the system quality due to the chromatic dispersion.

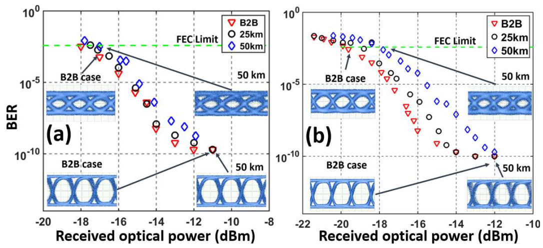


**Fig. 6:** (a) BER performance of 1533.46 nm and (b) 1535.03 nm channel for B2B, 25 and 50 km fiber transmission

In addition, we also investigated the quality of bust mode transmission and its effect on out-of-channel (OOC) power spectral density. This is an important parameter of a TWDM PON transmitter, determining the level of interference on adjacent channels, in both static and dynamic operation. For this test, a burst of 10 Gb/s data as well as gating signals (burst envelope) are generated. As before, the data signal is applied to the RF section, while the gate is used to turn the SOA section on and off. This blocks any light that might be generated by the transmitter between the data packets. The length of the gate signal is set to 62.5 µs with a 50% duty cycle. There is a 100 ns delay between the start of the gate and data burst to avoid any distortion. Fig. 7 (a) shows the oscilloscope trace of the burst signal, while Fig. 7 (b) shows the power spectral density of the burst signal, measured within a 15 GHz resolution, and the corresponding OOC1 and OOC2 bands set by the NGPON2 TWDM standard. The plot shows that the device performs well within the limits set by the specification[9]. Such stable operation from a DML in burst-mode operation, is achieved thanks to the PIC architecture and continuous injection from the master laser (locking the slave).

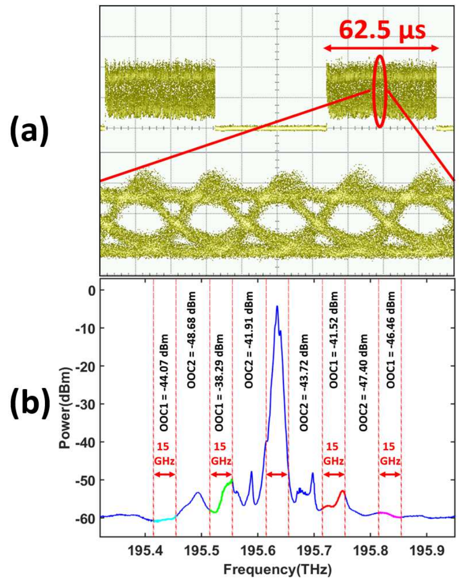


**Fig. 7:** (a) Data burst trace and corresponding eye, (b) PSD of the transmitter operating in a burst mode.

## Conclusion

A directly modulated 8-section PIC transmitter for application in TWDM PON is demonstrated. We show that by individual bias control over sections four wavelength channels, spaced by 100 GHz, can be generated. Furthermore, optimisation of the injection power provides a chirp mitigation technique, extending the reach. Using this feature, an error free transmission of 10 Gb/s data signal over 50 km of SMF, was demonstrated. A successful burst generation was also shown, exhibiting a low adjacent channel interference due to the OOC emission.

## Acknowledgements

This work has been supported in part by research grants from the Irish Research Council (IRC) EBPPG/2018/53 and from Science Foundation Ireland (SFI) under grant numbers 15/CDA/3640, 13/RC/2077_P2, 12/RC/2276-P2 and 18/RI/5755.

## References


[1] L. A. Coldren, *et al.*, “High performance InP-based photonic ICs—A tutorial,” *J. Lightw. Technol.*, vol. 29, no. 4, pp. 554–570, Feb. 2011.

[2] A. Dixit, *et al*., “Wavelength switched hybrid TDMA/WDM (TWDM) PON: A flexible next-generation optical access solution”, *2012 14th International Conference on Transparent Optical Networks (ICTON)*. IEEE, 2012.

[3] C. Lin, *et al.*, “Reduction of frequency chirping and dynamic linewidth in high-speed directly modulated semiconductor lasers by injection locking.” *Electron. Lett., vol* 20, no. 25, pp. 1073-1075, 1984.

[4] Y. Okajima, *et al.*, “Experimental observation of chirp reduction in bandwidth-enhanced semiconductor lasers subject to strong optical injection.” *Optics Comm.,* vol. 219, no. 1-6, pp. 357-364, 2003.

[5] N. Olsson, *et al.*, “Chirp-free transmission over 82.5 km of single mode fibers at 2 Gbit/s with injection locked DFB semiconductor lasers” *Journal of Lightw. Technol,* vol. 3, no. 1,pp. 63-67, 1985.

[6] J. O'Carroll, *et al.*, “Transmission over 50 km using a directly modulated integrated two-section discrete mode laser at 1550 nm”, In *2013 Conference on Lasers & Electro-Optics Europe & International Quantum Electronics Conference CLEO EUROPE/IQEC*, pp. 1-1. IEEE, 2013.

[7] G. Jain, *et al.*, "Directly modulated photonic integrated multi-section laser for next generation TWDM access networks." *45th European Conference on Optical Communication (ECOC 2019)*, IET, 2019.

[8] G. Jain, *et al*., “Design optimization for semiconductor lasers with high-order surface gratings having multiple periods.", *J. Lightw. Technol.,* vol. 36, no. 22, pp. 5121-5129, 2018.

[9] Recommendation ITU-T G.989.2 (2019). https://www.itu.int/rec/T-REC-G.989.2