Monolithically integrated filtered-feedback multi-wavelength laser with Mach-Zehnder modulators

Jing Zhao[1], Klaas Dijkstra[2], Michael J. Wale[3], Peter Maat[2], Meint K. Smit[1], Xaveer J.M. Leijtens[1]

[1] Eindhoven University of Technology, COBRA, Photonic Integration Group
P.O. Box 513, 5600MB Eindhoven, the Netherlands
[2]Astron Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, the Netherlands
[3] Oclaro, Caswell, Towcester, Northamptonshire, NN12 8EQ, U.K.

***Abstract* - A novel multi-wavelength transmitter monolithically integrated on InP is presented. The device consists of four-channel filtered-feedback multi-wavelength laser and four Mach-Zehnder modulators. The design of the circuit and experimental results will be discussed.**

***Keywords* - Photonic Integrated Circuits; multi-wavelength; transmitter.**

I. INTRODUCTION

Progress in wavelength-division-multiplexing (WDM) technologies for broadband telecommunication systems has raised the demands for integrated laser-modulator transmitters, especially multi-wavelength transmitters, due to their efficiency in increasing the flexibility and reducing the cost of WDM systems. Different integrated transmitters have been reported, such as multi-section hybrid silicon DBR lasers integrated with electro-absorption modulators [1], tunable distributed feedback (DFB) lasers with Mach-Zehnder modulators on InP [2], and tunable distributed Bragg reflector (DBR) laser arrays with electro-absorption modulators (EAMs) on InP [3].

Here we present a novel monolithically integrated multi-wavelength transmitter based on filtered optical feedback and using Mach-Zehnder modulators on InP material. This transmitter is designed in the mature and stable surface ridge active/passive InP-based integration technology of Oclaro Ltd. (UK) [4], and fabricated through a generic multi-project wafer (MPW) run on the JePPIX platform [5].

This paper describes the design and characterization of the transmitter chip as well as the characterization of the analog photonic link formed by one channel of the integrated laser and modulator.

II. INTEGRATED LASER-MODULATOR DESIGN

The circuit design is divided into two parts: the design of a filtered-feedback multi-wavelength laser (FFMWL) [6], and the design of the four identical Mach-Zehnder modulators that are connected to the laser. Fig.1a shows the schematic layout of the transmitter. The FFMWL part consists of four Fabry–Pérot (FP) lasers each formed by a SOA with two multimode interference reflectors (MIRs) [7]. And the FP lasers are wavelength locked through a feedback section with an arrayed waveguide grating (AWG) and a common MIR. The FFMWL can thus emit simultaneously at four channels, of which the lasing wavelength is determined by the AWG. At the left side of each FP laser, the light is routed to a Mach-Zehnder (MZ) modulator for each wavelength channel. Fig. 1b is the microscope photograph of the fabricated multi-wavelength transmitter. This device uses an AWG with 3 inputs and 5 outputs with wavelength channels spaced at 200 GHz (1.6 nm@ λ=1550 nm), and a central wavelength of 1550 nm. The central channel of the 3 inputs ends in the common 1-port MIR to produce the feedback; the other two channels are for characterization only. On the other side, 4 outputs are connected to 4 channels of the FP lasers while phase shifters (PHS) are included to adjust the phase of the feedback. Each FP laser has a 320-µm-long gain section in a 750-µm-long cavity, which produces a 50-GHz FP mode spacing [6]. With curved waveguides the outputs of the FP lasers are coupled to the MZ modulators and each of the modulated signals is guided to the 7^{o} angled anti-reflective coated facet. Two 1×2 multimode interference (MMI) couplers are used as power splitter and combiner for the MZ modulator. The phase shift function in the modulator arm is achieved with a 1-mm-long lumped-element electrode on a 1.2-µm-wide deeply-etched ridge waveguide, through p-i-n doped epitaxial layers which contain the InGaAsP MQW core. The metallization and the waveguide cross-section of the phase shifters are according to the Oclaro design. The two modulator arms can be independently driven. The footprint of the transmitter chip is 2×4 mm^2.

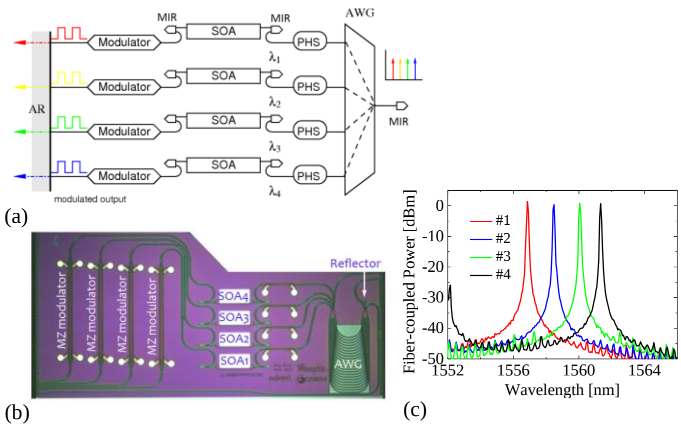

Figure 1 (a) Schematic of the 4-channel transmitter device and (b) Microscope photograph of the realized device. The chip dimension is 2×4 mm^2. (c) Superimposed lasing spectra of the four lasers channels.

III. CHARACTERIZATION

The device is mounted on a copper cold finger platform which in turn is mounted on a thermo-electric cooler (TEC), as shown in Fig. 2a. The TEC and a thermistor are mounted on the same cold finger to stabilize the chip at 20ºC during all the measurements. The chip is 23º tilted in order to allow the lensed fiber coming straight from the bottom in the photograph to couple the light properly from the waveguide with 7º facet angle.

All the electrodes on the transmitter chip have been wire bonded to their corresponding tracks on a custom designed PCB board which is surrounding the copper platform (Fig. 2a). Lasers and phase shifters are connected to laser current driver and voltage control, respectively. For the modulators, the electrodes on input side are bonded to the coplanar waveguide (CPW) on the PCB, where the GSG RF probe can be placed for high frequency measurement, and the electrodes on the output side are bonded to 50 Ω impedance terminations arranged on the PCB, as Fig. 2b indicates.

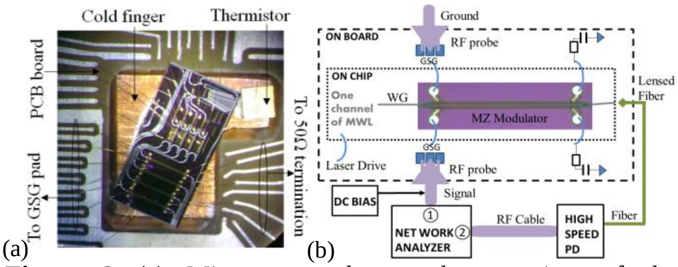

Figure 2 (a) Microscope photograph top view of the transmitter wire bonded with testing board; (b) Schematic for one channel transmitter connection in the photonic link measurement setup.

Firstly four channels of the multi-wavelength laser are measured consecutively with all the modulator electrodes open. Fig. 1c shows the measured lasing spectra with the laser injection current in the range of 75mA to 85mA. A similar measurement on such a FFMWL has been discussed in detail in [6]. Here we concentrate on the measurement with modulators.

The four laser channels operate on wavelengths spaced 200GHz, with slightly different output power. Here we take channel 1 as an example. When the injection current is 85mA, the laser has a CW single wavelength output at 1556.8 nm, with 1.36 dBm optical power in the fiber as measured by an HP 81618A power meter. With this laser as input, the MZ modulator light versus voltage (LV) transfer function is measured for each arm of the modulator, while the other arm is grounded, and the result is plotted in Fig. 3a. The modulator imbalance V_{IMB}, DC extinction ratio ER_{DC}, and voltage for π phase shift, V_{π}, are labeled in the figure. $ER_{\mathrm{DC}}\approx 21$ dB, and $V_{\pi}\approx 4$ V, are similar for all 4 channels of the transmitter, whereas the V_{IMB} varies from 0.3 V to 2 V, due to the imperfect symmetry of the two arms of the modulators.

The small-signal RF EO measurement setup is shown in Fig. 2b. A CW single wavelength output from the FFMWL is fed into the MZ modulator. One arm of the modulator is grounded, and the other arm is connected to the port 1 RF output of the electrical network analyzer (ENA), through GSG RF probe. The modulated optical output coupled from the fiber is routed to a high-speed photodiode (R2560A). The detected signal is sent back to port 2 of the ENA. Thus a microwave photonic link is built [8]. The bias voltage is set to the quadrature point of the modulator, and the input RF signal frequency is swept from 50 MHz to 10 GHz, with -10 dBm power. With the modulator output power at -2 dBm in the fiber, which was the maximum value at the quadrature point, an intrinsic analog photonic link gain is measured around -45 dB up to 5 GHz as shown in Fig. 3b. Although the link gain is largely limited by the output power of the integrated laser, it can be improved by introducing a push-pull drive configuration, optimizing the PCB and using more accurate calibration. This will also help to increase the bandwidth, as the bond wires in this first-version PCB are rather long.

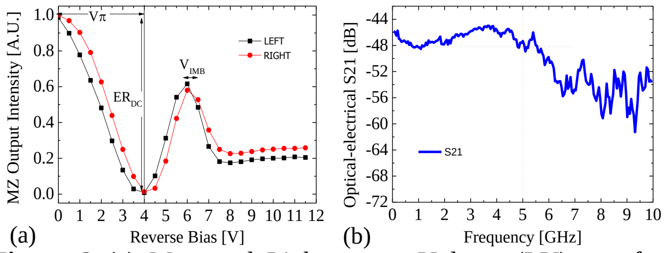

Figure 3 (a) Measured Light versus Voltage (LV) transfer function (alternate arm at 0V); (b) Small signal optical-electrical S21 for the integrated laser-modulator formed photonic link.

IV. SUMMARY AND ACKNOWLEDGEMENT

The monolithic integration of an FFMWL with MZ modulators on InP is reported for the first time. Characterization of the laser-modulator transmitter mounted on a PCB board was carried out. The modulators have a V_{π} around 4V and DC extinction ratio of 21 dB. The photonic link formed by this transmitter has an intrinsic gain around -45 dB with 5 GHz bandwidth.

The authors acknowledge the support of the Smart Mix Program of the Netherlands Ministry of Economic Affairs and the Netherlands Ministry of Education, Culture and Science.

REFERENCES

[1] M. Sysak, *et al.*, "Integration of hybrid silicon lasers and electro-absorption modulators," *Opt. Exp., vol. 16, pp. 12478–12486, 2008*

[2] Y. Shibata, "Integration of semiconductor Mach-Zehnder modulator with tunable-wavelength laser diode" *Proc. conference on Lasers and Electro-Optics (CLEO2011)*, May 1-6 2011, Maryland, US

[3] R. Nagarajan, *et al.*, "400 Gbit/s (10 channel ×40 Gbit/s) DWDM photonic integrated circuit", *Electron. Lett*., vol.41, pp. 347-349, 2005

[4] A. J. Ward, *et al.*, "Widely Tunable DS-DBR Laser With Monolithically Integrated SOA: Design and Performance", *IEEE J. Quantum Electronics* vol. 11, no. 1, Jan./Feb. 2005

[5] X. Leijtens, "JePPIX: the platform for InP-based photonics," *IET Optoelectronics*, vol. 5, pp. 202—206, 2011.

[6] J. Zhao, *et al.*, "Monolithic Integrated Filtered-feedback Multi-wavelength Laser" *Proc. Optical Fiber Communication Conference (OFC 2012)*, March 4-8, 2012, Los Angeles, California, US.

[7] E. Kleijn, *et al.*, "MMI reflectors with free selection of reflection to transmission ratio," *Proc. the 15th Annual Symposium of the IEEE Photonics Benelux Chapter*, Nov.18-19, 2010, Delft, The Netherlands.

[8] C.H. Cox, "Analog Optical Links Theory and Practice", 2004, Cambrighe University Press.