InP Monolithically Integrated Transmitters based on High Speed Directly Modulated DFB Lasers

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(Invited paper)

***Abstract*—In this paper we summarize results concerning high-speed integrated multi-wavelength transmitters fabricated using a generic InP integration platform. The photonic integrated circuits (PICs) include tunable directly modulated DFB lasers emitting in the C-band, monitoring photodetectors, MMI couplers and output spot size converters. The directly modulated lasers, designed in order to fit within a 100 GHz grid, show a maximum 3-dB small signal bandwidth of 21 GHz and a tunability range of about 4 nm.**

In particular, we report an 8-channel transmitter showing operation up to 30 Gb/s per channel (for 200+ Gb/s applications) and a 4-channel transmitter capable of operating up to 34 Gb/s per channel (for 100+ Gb/s applications). Error free operation (bit error rates < 10^{-9}) is achieved for all the channels in all the cases.

***Index Terms*—Photonic Integrated Circuits (PICs), Monolithic integrated circuits, High speed transmitters, Distributed feedback lasers.**

I. Introduction

MULTIWAVELENGTH transmitters are useful in several applications ranging from short- to long-haul optical digital transmission, including data center networks, access networks, mobile backhaul and many others [1, 2]. In addition, they are also demanded in microwave photonics, where dense and parallel transmitter integration is envisioned for broadband wireless access networks, sensor networks, radar, satellite communications, instrumentation, warfare systems, and also beamforming [3-7]. Indeed, compact integrated high speed parallel transmission solutions are beneficial in various scenarios: for example, for directly connecting arrayed antennas, in order to enable the steering of the received signals at the receiver side, in hybrid fiber radio systems, where wavelength division multiplexed (WDM) systems can help in deploying cost effective network solutions, and others [9, 10].

Previous implementations of locked distributed feedback laser (DFB) arrays [11-13] have demonstrated the feasibility of this approach in order to reduce the number of per-wavelength transmitters, where, however, each laser is fixed per fabrication and must be optically modulated through a dedicated component. In this context, a bank of properly coupled directly modulated lasers (DMLs) allows to realize a simplified yet effective transmitter architecture, suitable in several application fields where the monolithic integration of multiple modulated sources on the same chip can lead to very compact devices and also to component cost reduction. In [14] an array of 8 directly modulated lasers used for transmission at 10 Gb/s on 2 km in C-band has been reported, using a bar of lasers without any additional integrated coupling structure. In [15] an array of 4 directly modulated lasers with a bandwidth of 17 GHz suitable for 25 Gb/s modulation has been reported including 30 km transmission in the low fiber dispersion region around 1300 nm (O-band). Very recently, a 6-channel tunable transmitter capable of 30 Gb/s per channel fabricated in an open access InP foundry has been reported [16]. However, in this last case, the use of Mach-Zehnder modulators together with tunable coupled-cavity lasers increases the number of optical components to be integrated, fed and controlled.

Recently, we reported an InP-based photonic integrated transmitter realized on a generic integration platform with eight 100-GHz-spaced channels in the C-band exploiting broadband directly modulated DFB lasers [17]. We showed the PIC operation demonstrating error-free operation for signals in back-to-back up to 20 Gb/s per channel and also the transmission on standard single mode fiber (SMF) up to 2.1 km.

Despite such a short transmission distance cannot be sufficient for a number of optical digital communication transmission applications (where optical transponders including external modulators are required to reduce the signal chirp), it fits well with a number of applications in the microwave field, where the parallel transmission of large portions of the analog frequency spectrum is required. This includes beamforming,

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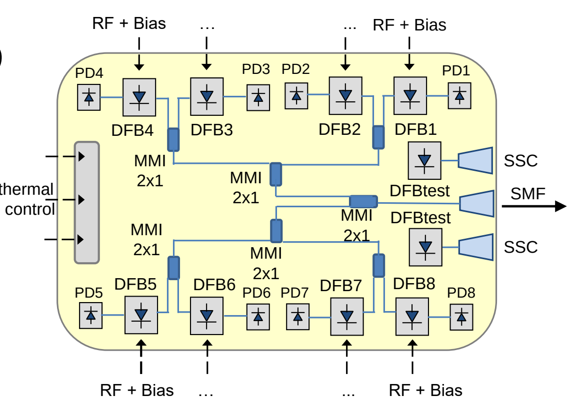
antenna remoting and other applications in the defense/security field. In this context, in particular, a larger operating bandwidth of the devices can be desirable.
In this invited contribution, indeed, we report more recent results obtained with transmitter PICs having similar structure of the device in [17], but realized in an additional fabrication run, by the same generic foundry, which returned broader bandwidth lasers. In particular, the paper is organized as follows: in Section II, an eight-channel transmitter working up to 30 Gb/s per channel is described. In Section III, a faster four channel PIC operating at up to 34 Gb/s per channel is reported. We then draw conclusions in Section IV.

II. 8-Channel Multi-wavelength Transmitter

The PICs have been fabricated exploiting the InP platform at Fraunhofer HHI using their generic integration technology [17], [19] in an additional multi-project wafer run, in respect of the one used for the devices reported in [17]. In respect of the previous fabrication, the foundry improved the ohmic p-contact formation which was non-optimal. This, as we report in the following, substantially improved the frequency response of the laser. A picture of the 8-channel integrated multi-wavelength transmitters is reported in Fig. 1 together with a schematic diagram. The circuit design is the same as in [17]. The overall footprint is 6×4 mm^2. Eight directly modulated DFB lasers are butt coupled on both sides to passive waveguides so that one output of each laser is terminated onto an integrated monitoring photodetector (PD), and the other one is connected to the 2×1 coupling MMI. Cascaded MMI-based couplers combine all the lasers. The single output waveguide terminates into a spot size converter (SSC). The SSC widens the waveguide mode to maximize the overlap with a standard single mode fiber size. The SSC is adiabatic in order to minimize distortion and loss. The output facet is anti-reflection coated to minimize reflections considering also that the SSC is orthogonal to the output facet. A number of additional electrical contacts are present on the chip surface so as to help in wire bonding and mounting the chip.

a)



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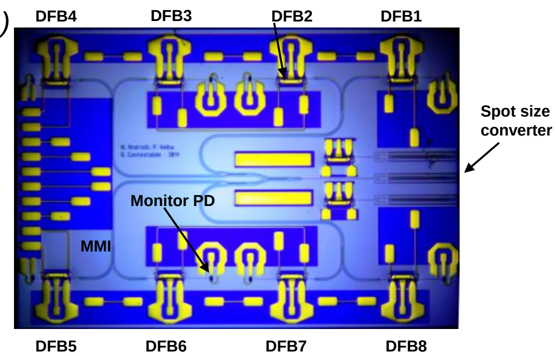
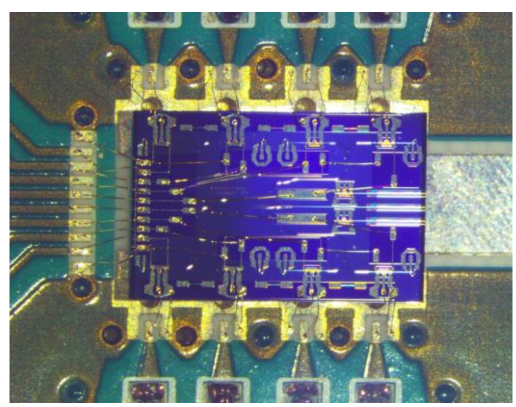


Fig. 1. (a) Schematic diagram of the PIC; (b) microscope picture of the fabricated eight-channel transmitter. Footprint: 6×4 mm^2.

Each DML is a complex-coupled distributed feedback laser, which incorporates a twin waveguide formed by active InGaAsP multi-quantum wells and a quaternary bulk layer, and is 200 µm long [20]. The emission wavelength can be selected between 1530 and 1570 nm. An integrated heater allows an output wavelength tuning of around 4 nm.

In [17] we demonstrated that high-frequency printed circuit boards (PCBs) can be used to operate the integrated transmitter. These PCBs included surface mounted resistors in series with the respective laser for matching the line impedance, SMA ports for laser biasing and modulation, and a General Purpose Input-Output (GPIO) connector for laser wavelength thermal tuning. Gold wire bonds with a diameter of 25 µm have been used to connect both RF and DC pads. Ball bonding was performed with the ball placed on the PIC. Typical bond lengths are below 1 mm for RF pads and about 1.2 mm for DC pads to the PCB. Since only one level of metallization was available, on-chip wire bonding was also necessary to provide DC signals for thermal tuning to some devices.



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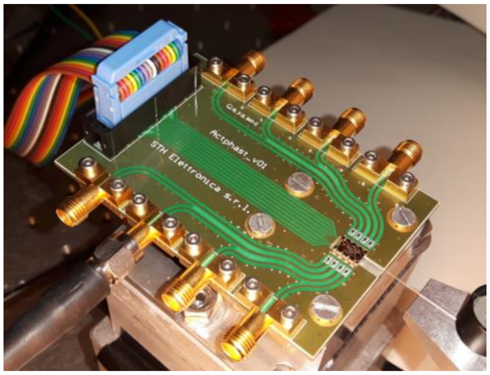

Fig. 2. Pictures of the PIC as mounted and wire bonded on the PCB (upper part) and of the whole PIC-PCB assembly during characterization (lower part). Surface mounted resistors can be observed on the PCB above and below the chip.

Fig. 2 shows details of the PIC wire bonding (top) and of the device mounted on the PCB (down). The whole PCB was placed on a heat sink and a Peltier cooler. To improve mechanical stability and thermal dissipation, the circuit was mounted on a Si submount directly attached to the heat sink.

Laser bias and modulating signals were supplied through the SMA connectors using bias-tees. This test vehicle mount assembly was useful for demonstrating error free multi-wavelength operation up to 20 Gb/s with the devices fabricated in [17] having 3-dB bandwidths in the range 12-14 GHz. We tried to mount the novel PICs in a similar way on the same PCBs, but, unfortunately, no one of the realized transmitters on PCB showed enough resulting overall bandwidth to properly operate the new chips. Therefore, all characterizations reported in the following have been performed channel-by-channel using a 40 GHz ground-signal-ground microprobe. The chips have been mounted on a metal chuck by means of a thermally and electrically conductive epoxy resin. The temperature, controlled through a thermo-electric cooler (TEC) below the metal chuck, was stabilized at 25 °C.

Spectra of the 8 lasers, after they have been thermally tuned on a 100 GHz (0.8 nm) grid in the spectral region 1554-1560 nm, are collected in Fig. 3, as recorded by a high resolution heterodyne spectrum analyzer with 40 MHz resolution (channel power is not an absolute value). Side mode suppression ratio (SMSR) is in excess of 55 dB for all lasers. An example of the tunability trend as a function of the supplied electrical power injected into the integrated heater is also reported in the upper part of the figure. The tunability efficiency is 120 mW/nm and follows a linear trend. The laser resistance vs. current trend is also reported on top of figure 3, showing that laser resistance in operational condition around 100 mA is 40 ohm.

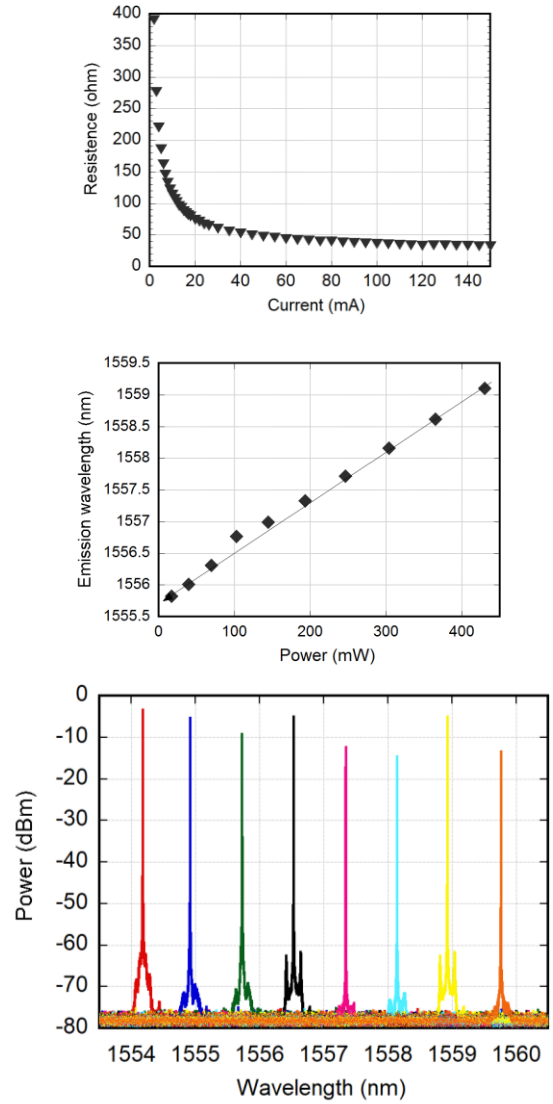

Fig. 3. On top, laser resistance vs. current trend. Tunability characteristic of a test laser. The efficiency is 120 mW/nm. Emission spectra of the eight lasers as recorded by a high resolution (40 MHz) optical spectrum analyzer (lower part). Wavelength spacing is 0.8 nm (100 GHz). Channel power is not an absolute value.

The nominal output power from each DFB is estimated to be 4 dBm as by foundry specification, whereas the measured output power from the chip is in the range -10 to -12 dBm for each laser. This gives a 14-16 dB total insertion loss for the cascade of MMIs, the propagation across the chip, and the fiber coupling. More in detail, given that the spot size converter contributes for a loss of around 2 dB and the propagation loss is about 1 dB/cm, the MMIs have about 1 dB excess loss each, in line with the values expected from the specifications.

The frequency response of the DMLs has been measured through a 50 GHz Network Analyzer using an external 32 GHz pin photodiode after an automatic calibration procedure for the electrical path. All the lasers have a similar frequency response with a bandwidth in the range 17-18 GHz at a current bias of 110 mA (i.e., the operating current used for the BER measurements reported in the following). A comparison of laser bandwidths for the transmitter reported in [17] and the most recent fabrication reported in this paper is shown in Fig. 4 for similar current values. An improvement of bandwidth at 3-dB of about 5 GHz can be appreciated.

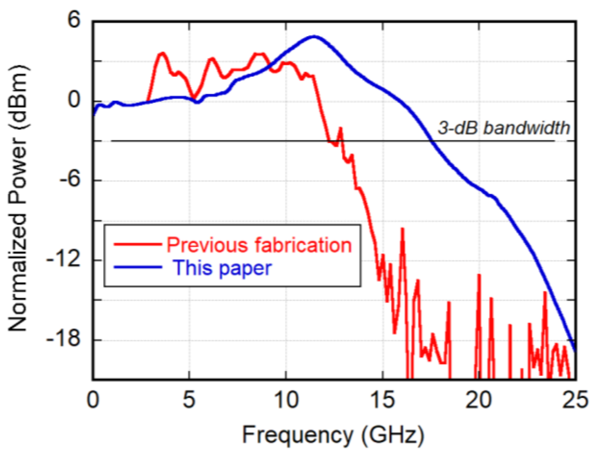

Fig. 4. Comparison of DFB normalized modulation response for a sample laser reported in [17] and a sample laser in the eight-channel transmitter presented in this paper (Bias current is 110 mA in both cases).

The monitor photodetectors have been also characterized using the RF probes and show a bandwidth of 15 GHz and a responsivity of around 0.8 A/W.

To test the digital response of the transmitter, we used the setup sketched in Fig. 5: a bias-tee was used to provide both the bias current (of about 110 mA) and the 2^{31}-1–long non-return-to-zero (NRZ) modulated pseudo-random-bit-sequence (PRBS) generated by the pattern generator at different data rates and amplified to around 3.3 V peak-to-peak (Vpp). These values allow to maximize the extinction ratio and at the same time optimize the eye diagram shape. The bias and Vpp working points were then slightly adjusted channel by channel and at varying the bitrates.

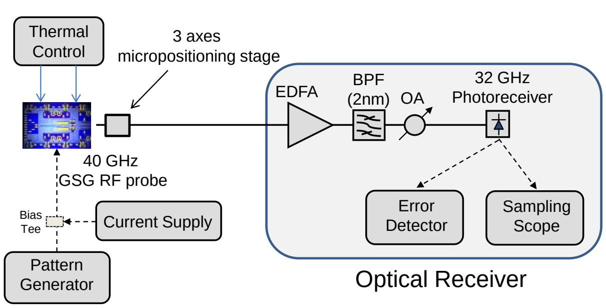

Fig. 5. Experimental setup for the BER measurements. EDFA: erbium doped fiber amplifier; BPF: band pass filter; OA: optical attenuator.

A standard single mode fiber (SMF) has been attached to a three axes micropositioner stage with optical power feedback control to guarantee optimal alignment throughout the transmission experiment. The signal collected into the fiber is then sent into an amplified optical receiver made by an erbium doped fiber amplifier (EDFA), a 2 nm band pass filter (BPF), an optical attenuator (OA) and a 32 GHz amplified photoreceiver. The received electrical signal was then analyzed by an electrical sampling scope with a 56 GHz optical head and by an error detector.

Fig. 6 reports the BER for all the 8 channels at 28 and 30 Gb/s, i.e., the maximum operating bitrates where all the channels were running error free (namely, with BER<10^{-9}). Two sample eye diagrams are also reported in the upper part of the figure showing clear eye data opening at both frequencies. In respect of [17], where error free operation was recorded up to 20 Gb/s, a 10 Gb/s capacity gain per channel can be appreciated. Power sensitivity (at a BER=10^{-9}) is in the range -5.8 to -3 dBm for the 28 Gb/s channels, while it is in the range -3.6 to -1.5 dBm for the 30 Gb/s ones.

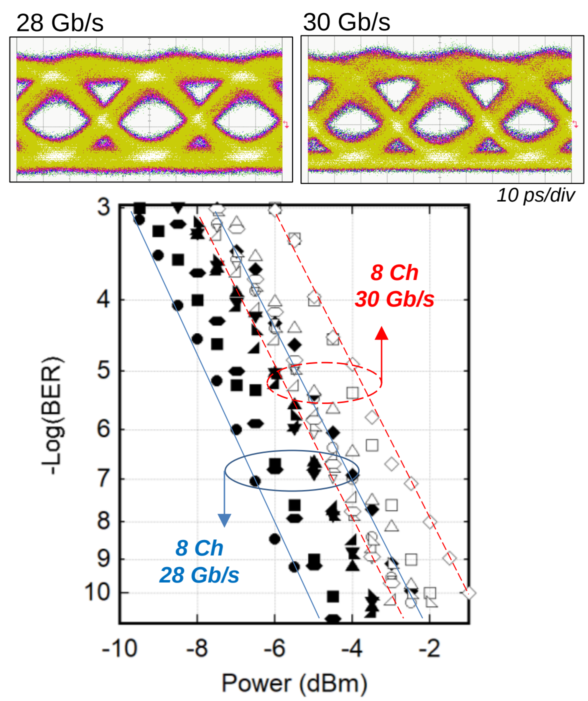

Fig. 6. Sample 28 and 30 Gb/s eye diagrams recorded with a 56 GHz sampling head (upper part). Collection of all the eight BER curves as a function of the received power at 28 and 30 Gb/s (lower part).

III. 4-Channel Multi-wavelength Transmitter

In addition to the 8-channel transmitter reported in Section II, in the last fabrication run we also included a 4-channel design intended for implementing a short range 100 Gb/s+ compact WDM transmitter. The PIC, similar to the eight channel one, is shown in Fig. 7. Four DFB directly modulated lasers are coupled through two cascaded 2×1 MMIs to an output spot size converter. High resolution spectra of the laser emission, once wavelength tuned on a 100 GHz grid, are also reported in the bottom part of the figure. In the samples obtained by the multiuser fabrication we found all four lasers showing a larger small signal modulation bandwidth in respect to the eight channel PICs. A comparison is reported in Fig. 8. For similar bias currents (around 110-115 mA) a 3 GHz wider 3-dB bandwidth can be appreciated with all the lasers having 19-21 GHz small signal modulation bandwidth.

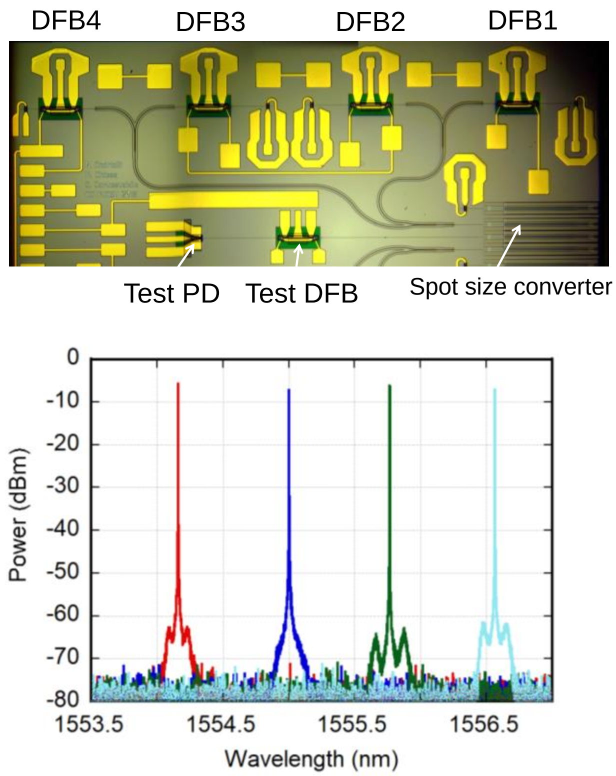

Fig. 7. Microscope picture of the fabricated four-channel transmitter (upper part). Footprint is 6×2 mm^2. Emission spectra of the four DFBs after tuning on a 100 GHz grid.

This allowed to perform higher speed BER characterizations using the experimental setup of Fig. 5 and similar driving conditions: bias current of about 110 mA, 2^{31}-1 –long NRZ PRBS data at around 3.3 V peak-to-peak (Vpp). In particular error-free generation of signals at 32 and 34 Gb/s was possible, obtaining the open eye diagrams reported in the upper part of Fig. 9. The related BER measurements are summarized in the lower part of the figure. The resulting 32 Gb/s sensitivity (at 10^{-9}) for all the channels was between -3 and -2.5 dBm, while the 34 Gb/s sensitivity was between -1.2 and -0.5 dBm.

All transmission measurements reported in this paper have been performed in back to back. It is known [21] that directly modulated lasers exhibit significant frequency chirp which can limit the transmission distance in optical communication systems. For instance, in [17] we found that only short-range (up to 2.1 km) transmission up to 15 Gb/s on standard single mode fiber was possible with the first version of the 8-channel transmitter. This was due to the combination of the signal frequency chirp and of the fiber chromatic dispersion, causing an error floor due to inter-symbol interference at a BER above 10^{-5} even at 20 Gb/s.

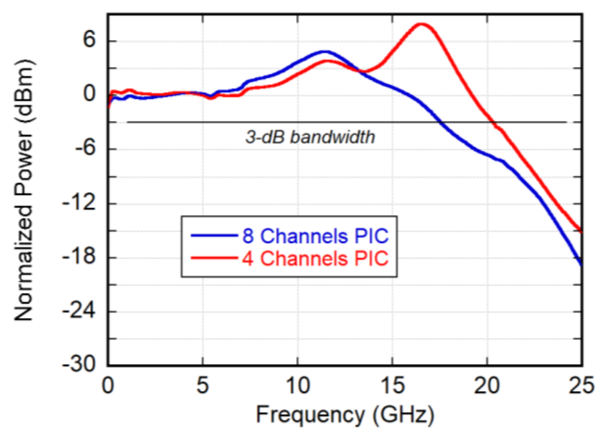

Fig. 8. Comparison of DFB normalized modulation response for a sample laser of the eight- and four-channel transmitters (Bias current is 110 mA in both cases).

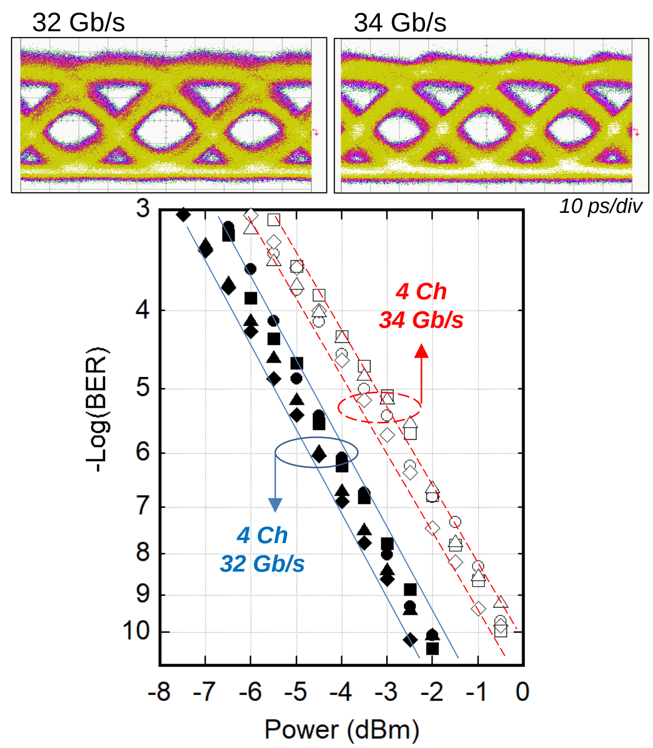

Fig. 9. Sample 32 and 34 Gb/s eye diagrams recorded with a 56 GHz sampling head (upper part). Collection of all the four BER curves as a function of the received power at 32 and 34 Gb/s (lower part).

We also characterized the signal chirp measuring the frequency shift of isolated pulses exploiting a complex spectrum analyzer (Apex AP2440). As reported in Fig. 10, showing the power and the instantaneous frequency chirp of an isolated pulse, the signal suffers from a significant blue shift near the pulse leading edge (up to 12 GHz) and a less pronounced red shift near the signal trailing edge. This chirp broadens the signal optical spectrum more than normally expected, and limits the attainable fiber transmission spans depending on the signal bitrate.

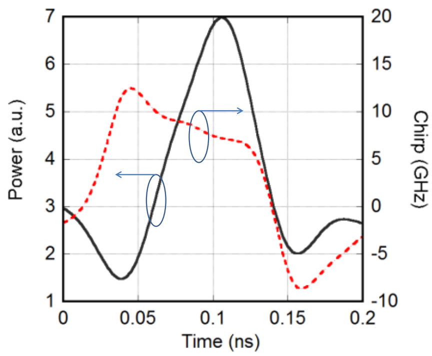

Fig. 10. Modulated DFB frequency chirp characterization. The black solid curve is the temporal shape of a pulse; the red dashed curve is the reconstructed chirp of the pulse by the complex spectrum analyzer.

Nevertheless, we recently demonstrated [22] that the 4-channel PIC can be used for implementing a 100 Gb/s (4×28 Gb/s) directly modulated transmitter capable of transmission up to 6.5 km of standard SMF when used in combination with a simplified DSP-free coherent detection scheme. In particular, in the paper, the use of simple low-pass electrical filtering allows to reject the spurious frequency modulation due to the lasers chirp, increasing the extinction ratio between the mark and space levels and thus the tolerance to the chromatic dispersion, in a chirp managed like fashion [23]. This simplified signal processing can be easily implemented by means of an analog electronic circuitry without any complex DSP. In the experiment, despite a larger operating bitrate was expected as just reported in this section, the bandwidth and sampling rate of the available real time scope (20 GHz and 50 GSa/s, respectively) limited the maximum operating bitrate to 28 Gb/s per channel and also the effectiveness of the low-pass filtering, suggesting that a fully analogue implementation could provide better results.

IV. Discussion and Conclusion

We have reported the characterization of two multi-wavelength integrated transmitters fabricated in an InP generic integration platform encompassing tunable DMLs, monitor PDs, and MMIs for signal multiplexing. The chip footprint of 6×4 mm^2 was dictated by foundry constraints and by the need to include test structures; the PIC area can be significantly reduced by removing the large pads used on each laser for testing purposes and the related monitoring photodetector, as well as placing the laser tuning pads close to the chip edge.

The 8-channel-transmitter has 8 emitting carriers in the C-band, with nominal wavelength ranging from 1554.2 to 1558.8 nm on a 100 GHz grid and a small signal modulation response of the DMLs of 17-18 GHz, allowing for error-free BER in back to back up to 30 Gb/s.

The 4-channel-transmitter, intended for 100 Gb/s+ applications has 4 emitting wavelengths in C-band, ranging from 1554.2 to 1556.6 nm on a 100 GHz grid, and a small signal modulation response of 19-21 GHz, allowing for error free BER in back to back up to 34 Gb/s. This last transceiver has been used for demonstrating transmission up to 6.5 km of standard SMF used in conjunction with a simplified DSP-free coherent detection scheme.

Regarding the chip design, while in this fabrication a series of MMIs 2x1 couplers has been used for laser coupling, the same function can be clearly also obtained by using a single array waveguide grating multiplexer, trading wavelength flexibility with a lower loss solution.

We outline that the results reported in this paper show the feasibility of complex and high frequency multi component photonic integrated circuits in state of the art open access foundries performing multi user wafer runs and using a mix of custom designed components and building blocks from the foundry library design kit. Unfortunately, following this (low cost) approach, only a limited number of fabricated samples are typically available to the users, which are also almost unaware of the technology processes and eventual related issues. As a consequence, some of the common device characterizations are often not possible. In our case, for example, because only a few transmitter samples were provided, we could not make any statistical consideration on the device performance and yield. In addition, we could not mount more devices on control boards to test simultaneous multichannel operation in order to characterize the potential electrical and thermal crosstalk. This means that, before moving into a possible development phase of the circuit, additional characterization work and also a reliable packaging are needed. Indeed, electrical, optical and thermal crosstalk are strictly dependent on the overall PIC and package assembly.

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