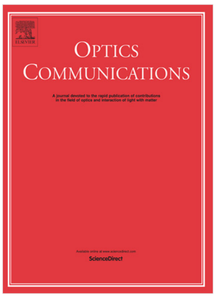

100 Gb/s (4×28 Gb/s) transmission in C-band by a directly modulated integrated transmitter and DSP-free coherent detection

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100 Gb/s (4×28 Gb/s) Transmission in C-band by a Directly Modulated Integrated Transmitter and DSP-Free Coherent Detection

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***Abstract*— We report C-band 100 Gb/s transmission (4×28 Gb/s) up to 6.5 km of standard single mode fiber exploiting an InP monolithically integrated WDM transmitter made by an array of four directly modulated DFB lasers on a 100 GHz spaced grid having a 3-dB bandwidth in excess of 20 GHz. To overcome the conventional chirp related chromatic dispersion limitation, we use the compact integrated transmitter in combination with a simplified DSP-free coherent detection scheme suitable for low cost, low power applications.**

***Keywords*— Photonic integrated circuits, Semiconductor laser arrays, High speed directly modulated lasers**

I. INTRODUCTION

WAVELENGTH Division Multiplexing (WDM) is one of the key technologies for large capacity short- and medium-reach optical links, even if WDM systems require a large count of photonic devices in order to implement the wavelength parallel transmission. In several applications which include data center networks, optical access, radio-over-fiber (RoF), mobile front/backhaul and others, it is desirable that the upgrade in transmission capacity is achieved without a significant increase in size, power consumption and cost of the equipment. Since multiple transmitters, receivers and mux/demux are required in WDM systems, photonic integration is the way for realizing compact optical transmitters and receivers with potentially lower cost and power consumption. Indeed, integrated transceivers with ever increasing aggregated capacity for long-haul, submarine, and metro optical networks are already largely deployed in last generation commercial coherent systems [1, 2]. In particular, in the transmitters they use arrays of distributed feedback (DFB) or tunable lasers together with external modulators and all the required additional optical components, showing high-end performance.

Nevertheless, there are a number of shorter reach applications where the use of compact directly modulated lasers (DMLs) can be a simplified solution of choice. This is the case of the massive data center connections, where O-band DMLs or vertical cavity surface emitting lasers (VCSELs) can be deployed, or RoF implementations. In this last case, to enhance the cost-effectiveness of mobile fronthaul networks it is crucial to utilize the full-duplex bidirectional transmission technique, using both 1.3-µm and 1.55-µm windows [3].

In this respect, 1.3-µm links using DMLs are not difficult to implement despite their intrinsic chirp, as standard single mode fibers (SMF) have zero or low dispersion in this spectral region. On the other hand, systems using DMLs operating in the 1.55-µm window are challenging, as the combination of intrinsic signal chirp and fiber dispersion can severely limit the attainable transmission distance [4].

For instance, in [5] an array of eight DFB lasers directly modulated up to 20 Gb/s with non-return to zero (NRZ) signals showed error free operation without dispersion compensation only up to 2.1 km SMF transmission, and in [6] up to 30 Gb/s in back-to-back. In the past, the use of chirp-managed directly modulated lasers, often in combination with electronic dispersion compensation (EDC) [7, 8], was proposed to overcome the transmission distance limitations. This approach, however, requires the use of lasers with peculiar chirp properties combined with extremely precise optical filtering at the transmitter or receiver side. In case of the use of EDCs, high speed electronic processing at the receiver is also required. The complexity increases in case of multi-wavelength operation, especially when photonic integration of the transmitter is considered.

In view of finding simplified and lower power, lower cost solutions, in this letter we report a 4-channel InP monolithically integrated transmitter made by tunable broadband directly modulated DFB lasers in the C-band and show that it can be used in combination with simplified DSP-free coherent detection schemes [9, 10] in order to conveniently overcome conventional transmission limitations. In particular, even if limited by experimental equipment (as detailed in the following,) we show that this solution is suitable for at least 100 Gb/s (4×28 Gb/s) transmission up to 6.5 km of SMF.

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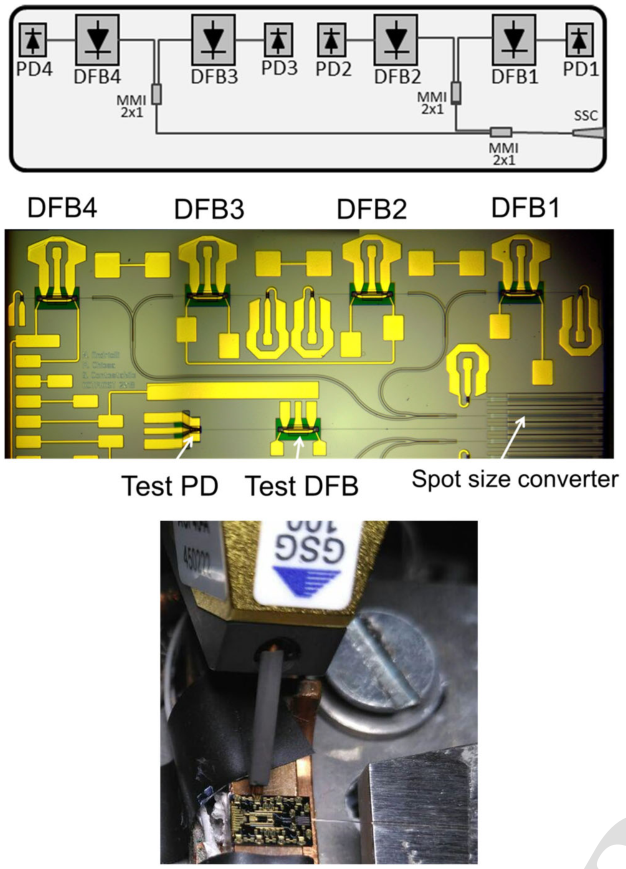

Fig. 1. Top: transmitter schematic. Center: picture of the 4-channel transmitter (footprint: 6×2 mm^2). Bottom: picture of the transmitter during operation.

II. MULTI-WAVELENGTH TRANSMITTER PHOTONIC INTEGRATED CIRCUIT

The photonic integrated circuit (PIC) has a footprint of 6×2 mm^2 and was fabricated in a multi-project wafer run, exploiting the generic integration platform provided by Fraunhofer HHI [11]. The schematic of the circuit and a picture of the corresponding portion of the realized chip are reported in Fig. 1. The PIC consists of four tunable DMLs working in the C-band with 100 GHz spacing. Each laser is a complex-coupled DFB incorporating a twin waveguide formed by active InGaAsP multi-quantum wells and a quaternary bulk layer [12]. Each laser is butt-coupled on both sides to passive waveguides, one connected to an integrated monitor photodetector (PD), and the other to a 2×1 multimode interference (MMI) coupler. The light from the MMI couplers is combined by means of a further MMI coupler and sent to the output port through a spot size converter (SSC), where it is collected by a SMF. Coupling is optimized thanks to the on-chip SSC and a three-axis micro-positioning stage, as depicted at the bottom of Fig. 1.

A characterization of the DFB lasers is reported in Fig. 2 for one sample laser, as the four DFBs were showing similar characteristics. Fig. 2a) reports the power vs. current trend: the threshold current is 18 mA and the maximum output power coupled into the fiber is -4 dBm. From this value, we estimate the on-chip insertion loss (IL) due to the propagation along the waveguides, the cascaded MMIs, and the fiber coupling. In particular, assuming that the DFB lasers emit the nominal output power of 4 dBm (as per foundry specifications), IL is estimated to be 8 dB. The electro-optic 3-dB bandwidth of the laser biased with a current of 100 mA, measured with a 50 GHz vector network analyzer, is 21 GHz, as reported in Fig. 2b).

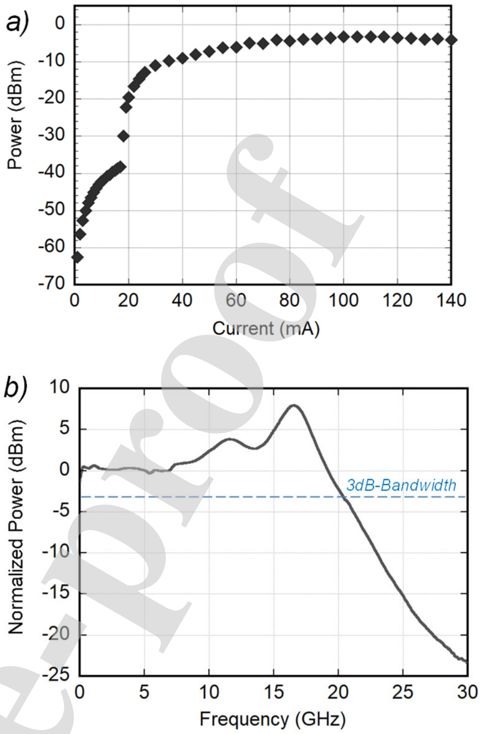

Fig. 2. DFB laser characterization: a) Power vs. current; b) Electro optic bandwidth at a current of 100 mA.

Fig. 3 reports the superimposed spectra of the 4 DFBs taken with a high resolution self-homodyne optical spectrum analyzer. The lasers are tuned using the thermal tuning section to exactly match a 100 GHz grid in the C-band. Side mode suppression ratio is in excess of 50 dB for all the lasers. A preliminary characterization of the 4-channel transmitter has been reported in [13], showing that it is suitable for error-free back-to-back transmission up to 34 Gb/s using on-off keying non-return-to-zero (NRZ) modulation.

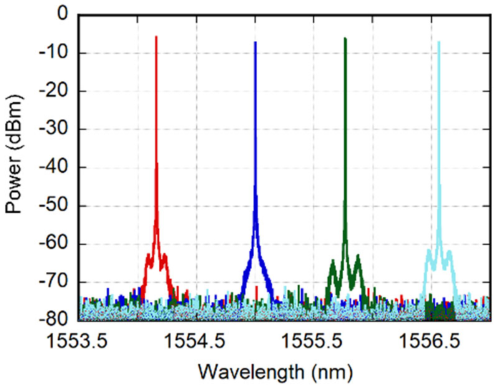

Fig. 3. High resolution spectra of the four 100-GHz-spaced lasers (Resolution bandwidth: 40 MHz).

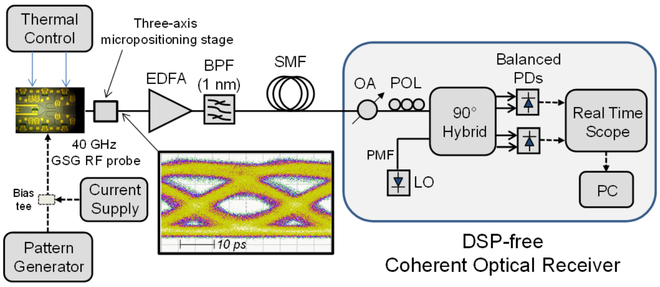

Fig. 4. Transmission experiment setup. Inset: eye diagram as recorded by a sampling oscilloscope at the PIC output. EDFA: Erbium doped fiber amplifier; BPF: band pass filter; SMF: standard single mode fiber; OA: optical attenuator; POL: polarization controller; LO: local oscillator; PD: photodetector; PC: personal computer.

III. TRANSMISSION EXPERIMENTAL SETUP AND RESULTS

The experimental setup for the transmission experiment is shown in Fig. 4. A 28 Gb/s NRZ $2^{31}-1$ pseudo-random-bit-sequence (PRBS) is generated by a pulse pattern generator (PPG) and coupled to the lasers bias current by means of a bias-tee. Both biases and the radio frequency signals are provided to the metal contacts of the DFB lasers through a coplanar probe with ground-signal-ground (GSG) contact geometry (see also Fig. 1). The transmitter is mounted on a copper metal chuck using a thermally and electrically conductive epoxy resin. The temperature is controlled and fixed at 25 °C, stabilized by means of a thermo-electric cooler (TEC) placed below the metal chuck. As measurements are performed on a bare chip, we characterize one laser at a time. Multiple laser operation and the use of the monitor PDs require packaging or mounting of the chip on a proper control printed circuit board (PCB) control board, as we showed in [5]. Unfortunately, in this case, due the limited number of samples available from the fabrication run and the larger required electrical bandwidth, we could not realize similar reliable PIC on board samples. The transmitter output signal is coupled into a SMF thanks to a 3-axis micropositioning stage. An eye diagram of the 28 Gb/s transmitted signal taken with a sampling oscilloscope is shown as an inset in Fig. 4. The attained extinction ratio is about 4 dB. The signal is amplified by an erbium doped fiber amplifier (EDFA) and filtered using a band pass filter (BPF) with a bandwidth of 1 nm. After transmission in different spans of fiber, it is sent into the receiver block.

The receiver is based on the DSP-free coherent detection scheme proposed in [9, 10] and makes use of a free-running DFB laser used as local oscillator (LO) (P_{LO} = 10 dBm). The LO wavelength is set in order to operate in a quasi-homodyne regime (i.e., it is detuned by approximately 500 MHz from the nominal frequency of the receiving signal). The signal and the LO are coupled by a polarization maintaining (PM) 90° hybrid coupler by means of PM patch-cords after polarization alignment. A variable optical attenuator (VOA) is used at the signal input port of the 90° hybrid in order to perform the bit error rate (BER) measurements as a function of the received power. The 90° hybrid coupler outputs are detected by two 40 GHz balanced PDs, in order to recover I and Q signal components, such a large bandwidth is not required by the scheme and was used as we had available those balanced receivers only. They are digitized in a real-time oscilloscope (20 GHz bandwidth, 50 GSample/s) and then processed offline.

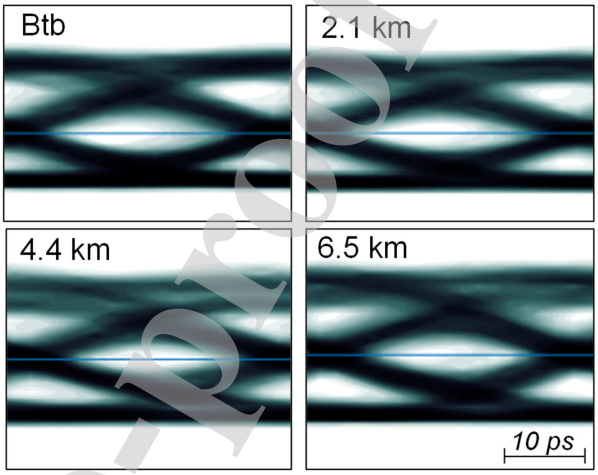

Fig. 5. Reconstructed eye diagrams for DFB4 in back-to-back and after transmission at various SMF lengths.

In the processing stage, the I and Q signals are first low-pass filtered, then squared and summed together. The electrical low-pass filtering (3-dB bandwidth of 18 GHz) has the effect to reject the spurious frequency modulation on the signal due to the lasers chirp, increasing the extinction ratio between the mark and space levels and increasing the tolerance to the chromatic dispersion, in a chirp-managed like fashion [9]. It is worth mentioning that this signal processing, even if carried out offline on the oscilloscope in this experiment, can be easily implemented by means of analog electronic circuitry without any complex DSP. We also note that the bandwidth and sampling rate of the digitizer available for the experiment (20 GHz and 50 GSample/s) limited in practice the effectiveness of the low-pass filtering, suggesting that a fully analogue implementation could provide improved results. Indeed, recently, a coherent detection scheme based on a "square-and-sum" analog processing similar to the one used here, has been proposed [9, 10], also achieving polarization-independent operation without exploiting polarization diversity.

In all the measurements, bias current and V_{pp} (Voltage peak-to-peak) are adjusted in order to optimize eye opening of the diagrams reconstructed by the coherent receiver. We found optimal bias currents between 96 and 103 mA and a V_{pp} = 3.5 V, those values yielding the best match with the selected receiver low-pass filter bandwidth. We measured the transmission performance after 2.1 (this was maximum attainable distance at 20 Gb/s using direct detection in [5]), 4.4 and 6.5 km. Sample software reconstructed eye diagrams for each transmission distance are reported in Fig. 5. Although some chromatic dispersion related inter-symbol interference can be seen on mark level at 2.1 km and on both digital levels at 4.4 and 6.5 km, a direct evaluation of the signal integrity cannot be clearly extrapolated from an analysis of the eye diagrams (even if the signal is still wide open after transmission). Bit error rate (BER) measurements, which are the most appropriate tool for a quantitative signal evaluation, are summarized in Fig. 6. BER measurements at 28 Gb/s for the back-to-back (btb) and for the signal after propagation along the 2.1, 4.4 and 6.5 km-long SMF spools are reported for each of the four on-chip lasers. In the btb case, the average sensitivity, measured at the Forward Error Correction (FEC) level of $2 \cdot 10^{-3}$, is around -13.5 dBm (with a power spread of about 1.5 dB between the best (DFB1) and the worst (DFB4) performing laser). After propagation there is a signal degradation so to reach an average sensitivity at FEC level of -10.5 dBm, and a power penalty in the range 2-4 dB with respect to the back-to-back results for the longer 6.5 km span.

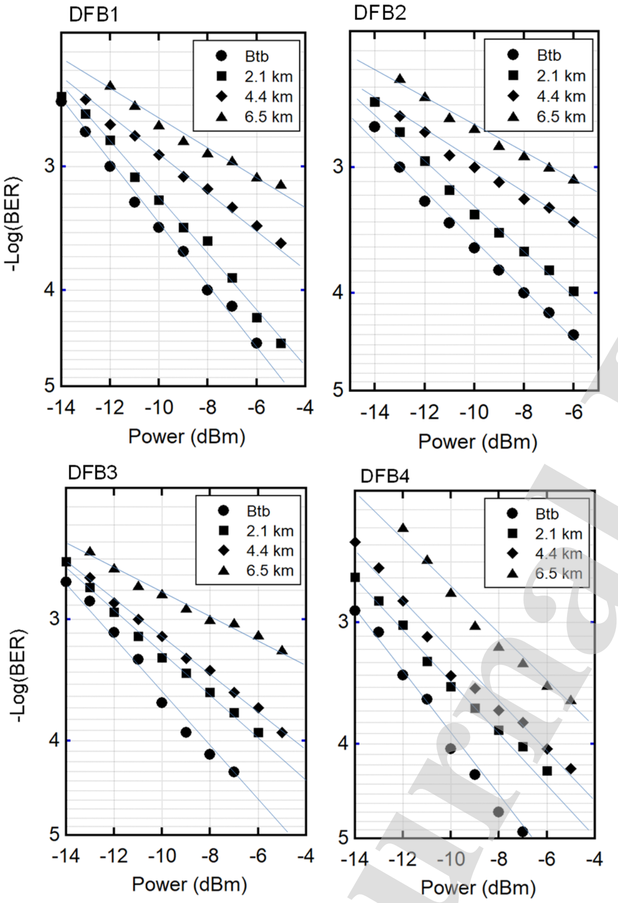

Fig. 6. BER vs. received power in back-to-back (Btb) and after propagation for the four directly modulated lasers.

IV. DISCUSSION AND CONCLUSION

We reported 100 Gb/s (4×28 Gb/s) transmission up to 6.5 km SMF in the C-band by using an array of directly-modulated lasers integrated on a PIC. The photonic integrated InP multi-wavelength transmitter has been fabricated exploiting a multi-project wafer run in a generic integration platform. In order to increase the attainable transmission distance in SMF, which is typically limited by the combination of the laser chirp and fiber chromatic dispersion, we used a simplified DSP-free coherent detection scheme that only exploits basic analogic processing. In addition, despite a single polarization version of the receiver has been implemented, polarization independence can be obtained by resorting to conventional polarization diversity schemes or one of the simplified schemes proposed for low cost applications in [10, 14]. Clearly, a larger transmission capacity can be attained using more efficient intensity multilevel modulation formats: for instance, 200 Gb/s transmission is possible in principle exploiting PAM-4 modulation. The results reported in the paper indicate that the proposed system is a compact and low-power solution suitable for short-reach, high-capacity scenarios. However, as we could not test the transceiver on a control board for simultaneous multi-channel operation, electrical and thermal crosstalk are still to be characterized in a future work where a reliable mount/packaging assembly is exploited. Moreover, if we consider that we were limited in the present experiment by the real time oscilloscope bandwidth, we have from the back-to-back characterization of [13] that a fully analogue implementation of the receiver could provide improved results in terms of both single channel capacity and attainable distance. Concluding, we would like to emphasize that the use of an EDFA and of a following bandpass filter, as in the experimental demonstration, is not strictly required. We used an optical amplifier to provide the required power on the suboptimal balanced photodetectors for performing the BER measurements. In principle, as we are using coherent detection, wavelength selection is not required [9, 10]. Moreover, by exploiting a more suitable receiver, amplification can be avoided. In this way, filter-less transmission on passive fiber links with a power budget fixed by the PIC output and the receiver sensitivity is clearly possible.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: