Ultra-Compact Monolithic Integrated InP Transmitter at 224 Gb/s with PDM-2ASK-2PSK modulation

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Abstract: We demonstrate a fully integrated InP transmitter at data rate up to 224Gb/s using 2ASK-2PSK modulation with polarization division multiplexing. We assess its suitability for cost-sensitive metropolitan networks with a large number of cascaded nodes.

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1. Introduction

Coherent technologies have been revolutionizing optical core networks and are expected to conquer a large market share in metropolitan and inter datacenter networks in the very near future. However, these segments are particularly sensitive to cost, and therefore to footprint and power consumption, while possibly facing stringent requirements from larger cascades of optical nodes than in core networks.

In order to contain cost, several chips can be co-packaged in the optoelectronic transmitter. For example, in [1], laser and modulator chips were co-packaged and produced optical data at 32 Gbaud. However, monolithic integration is expected to provide greater cost savings than co-packaging. The first generation of monolithically integrated transmitters was inspired by LiNbO3 modulators, relied on Mach-Zehnder modulators (MZM) and designed with Indium Phosphide (InP) technology. In [2], forty such MZMs were integrated with the corresponding lasers and an optical multiplexer, but the output symbol rate did not exceed 14.3 Gbaud per laser. More recently, a monolithic transmitter incorporating a MZM with a sampled grating-distributed Bragg reflector tunable laser, a semiconductor optical amplifier, and an absorber was reported and produced data streams at 10 Gbaud [3].

Here again, despite the high level of integration, the transmitter was limited in terms of modulation bandwidth by the MZM. To extend this bandwidth while further reducing footprint, short electro-absorption modulators (EAM) are natural candidates, but act primarily as intensity modulators. However, several EAMs in an interferometric arrangement can produce complex amplitude/phase modulation [4]. We built upon our two previous reports where we showed that a monolithic chip incorporating two EAMs and a laser source could be used to deliver 12.5 Gbaud binary phase shift keying (BPSK) [5] and 28 Gbaud polarization division multiplexed (PDM) -BPSK [6]. Both proof-of-concept papers fell short of the requirements of metropolitan optical terrestrial (only 40 km distance shown at 12.5 Gb/s).

In order to cope with these requirements, we propose here to engineer 2ASK-2PSK data streams by combining a monolithic chip, incorporating a single frequency laser source and two EAMs in a push-pull interferometric configuration, with a high performance digital-to-analog converter (DAC). We achieve a record 224 Gb/s bit-rate for monolithic transmitter. We then show the robustness of the generated signal to narrow filtering in optical nodes.

Figure 1: (a) Integrated 2ASK-2PSK transmitter schematic and (b) photography. (c) 4-level amplitude electrical signal (top) and theoretical output constellation (bottom). (d) Power spectral density of coherently received signal complex field with a Lorentzian fit.
2. Integrated coherent transmitter

Our integrated transmitter includes one distributed feedback (DFB) laser, 2 multimode interferometer (MMI) couplers, 2 phase shifters (PS), 2 EAMs and 1 output taper as represented in figure 1 (b). We rely on a two-arm interferometric structure schematized in figure 1 (a) to modulate light along the positive and negative parts of a single axis (e.g. the real axis) in the complex plane. To do so, we first assign a phase difference of π between the two arms of the interferometer by adjusting the current of the PSs. We drive the EAMs with complementary electrical waveforms, supplied by DAC of 8-bit resolution, followed by drivers delivering 3V peak-to-peak with 32GHz bandwidth. We engineer the waveforms such that they can alternatively take any of four equally-spaced voltage levels, instead of two levels in [5,6], so that the resulting optical carries twice as much bit-rate at unchanged symbol rate. Hence, after splitting and recombining via the MMI couplers, light from the DFB laser carries data with 2-level amplitude shift keying 2ASK, 2-level phase shift keying 2PSK, as depicted in the theoretical constellation of figure 1 (c). The output power of the monolithic transmitter was measured to be -5dBm. The circuit dimensions are 2.65 mm x 0.5 mm, making it the smallest reported 100Gbps-capable integrated transmitter, to the best of our knowledge. The extinction ratio between constructive and destructive interference states was above 20dB, which confirmed good power balance and phase control of the interferometer arms. We characterized the laser phase noise using a coherent receiver. To do so, the laser under test beats with a continuous wave narrow linewidth (< 100 kHz) external cavity laser. Figure 1 (d) shows the power spectral density (PSD) of the recovered field, centered on the offset frequency. A Lorenzian best fit to the measured data is also shown. The full width half maximum of the Lorenzian shape is 5.5 MHz without modulation, which is typical for a DFB laser.

3. Back-to-back characterization

We now assess the bit error rate (BER) performance of the system, for application in metropolitan networks. The test binary streams are Bruijn sequences of $2^{12}$-1 length and are used to generate 4-level and 2-level signals, corresponding to 2ASK-2PSK and BPSK modulation respectively, the latter serving as a reference to compare with the former. We start the noise sensitivity assessment by studying the performance of the transmitter in back-to-back operation. A polarisation division multiplexing (PDM) emulator is used after the transmitter to double the capacity and emulate the next level of integration. We use a coherent receiver, where the 8 outputs of the coherent mixer are detected by four balanced photodiodes, and an external cavity laser (ECL) as local oscillator. The signals at the output of the photodiodes are sampled at 80 GS/s by a Teledyne Lecroy real-time oscilloscope with 36 GHz of electrical bandwidth. A 100μs-long series of samples are stored and processed offline with a computer. After skew adjustments and normalization, polarization demultiplexing is performed using 25-taps half symbol-spaced equalizers with blind adaptation based on constant-modulus and multi-modulus algorithms for BPSK and 2ASK-2PSK modulation formats, respectively. After frequency offset compensation and carrier phase recovery, differential decoding is used to avoid cycle-slip errors. Finally, bit error count takes place. Figure 2 (a) and (b) show the results of the back-to-back (B2B) experiment in terms of Q²-factor versus OSNR in 0.1 nm for PDM-BPSK and PDM-2ASK-2PSK signals, respectively, at different baud rates ranging between 16 and 56 Gbdu. Insets in figure 2 (a) and (b) show two exemplary constellations obtained with our integrated transmitter. All PDM-BPSK measurements show performances well above 6.25dB Q²-factor which correspond to the soft-decision (SD)-forward error correction (FEC) threshold with 20% overhead. With the format PDM-BPSK, good performance was obtained up to 112 Gb/s, without considering cascades of optical filters. In contrast, PDM-2ASK-2PSK provide increased data rate up to 224 Gb/s. Moving to PDM-2ASK-2PSK doubles the spectral efficiency, but naturally affects the sensitivity to noise, by ~7dB (Q=6.25dB), as expected from theory. Besides, whatever the format, theory predicts 5.4dB
reduction of the tolerance to noise when changing the symbol rate from 16 Gbaud to 56 Gbaud. We measure 7 and 9 dB reduction, with PDM-BPSK and PDM-2ASK-2PSK modulation formats, respectively, at the SD-FEC limit. Optical spectra of signals at 16.2 and 56 Gbaud are presented in figure 2 (c). One can depict in both spectra the suppression of the optical carrier around 1540 nm (below 2 dB). The absence of side lobes at 56 Gbaud can be attributed to the limited modulation bandwidth.

4. Metropolitan network implementation

In metropolitan networks, specific challenges arise from travelling inside long cascade of transparent optical nodes. Such node incorporate either one or two wavelength selective switch(es) (WSS), depending on the node architecture, broadcast and select, or route and select, respectively [7]. In high capacity WDM systems compliant with the standard 50GHz channel grid, the filter response of WSS often distort the spectral content and can create significant penalties. To evaluate these penalties, we feed the signal of our transmission into a re-circulating loop [as shown in figure 3 (a)]. It incorporates a span of standard 100km-long fiber. It is longer than typical metro spans but does not generate any significant penalty from nonlinear effects, and can emulate the high loss of a metro span (25 dB). The loop also includes erbium doped fiber amplifiers (EDFAs) and one node, formed by two flex-grid WSSs. The signal launch power has been optimized to +4dBm. The PDM-2ASK-2PSK modulation format is compared with PDM-BPSK modulation format with two channels spacing of 50 and 100GHz. The maximum number of cascaded WSSs and spans are presented in figure 3 (b) as a function of the raw data rate, including the FEC overhead. At low data rate bit/symbol, a large number of WSS could be cascaded, preferably with PDM-BPSK [e.g. up to 149 (7400 km) and 129 (6400 km) at 32 Gb/s, with 50GHz and 100GHz grids, respectively]. Nevertheless and not surprisingly, symbol rates greater than 50 Gbaud are heavily penalised by the allocation along the 50 GHz-grid limiting the number of cascaded WSSs or the data bit rate well below 100 Gb/s with this format. Using our proposed PDM-2ASK-2PSK format, the transmission distance is more impacted by noise accumulation (as discussed in fig. 2), however higher data bit rate can be transmitted while surviving the cascade of WSSs. Over the standard 50 GHz grid, at the highest rate measured of 224 Gb/s, 5 WSSs in a row can still be managed. At 100 Gb/s net rate (120Gb/s total rate, when including 20% FEC overhead), PDM-2ASK-2PSK survives through a series of 24 WSSs, whereas PDM-BPSK fails to remain above FEC threshold even though one WSS.

5. Conclusion

We have demonstrated a fully integrated InP transmitter that generates a record capacity 224 Gb/s, using PDM-2ASK-2PSK modulation. Compared to PDM-BPSK, this modulation scheme is found particularly promising for low-cost 100Gb/s in a metro environment when cost, footprint, power consumption, and long series of optical nodes are true concerns.

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6. References