8.5 Tbps Net SiP O-band Coherent Transmission over 10 km Using a Quantum-Dot Mode-Locked Comb Laser

Santiago Bernal[1,*], Mario Dumont[2], Essam Berikaa[1], Charles St-Arnault[1], Yixiang Hu[1], Ramon Gutierrez Castrejon[1,3], Zixian Wei[1], Antonio D'Errico[4], Alessandra Bigongiari[4], Luca Giorgi[4], Stefano Stracca[4], Robert Brunner[4], Stephane Lessard[5], Fabio Cavaliere[4], John Bowers[2], and David V. Plant[1]

[1]*Dept. of Electrical and Computer Engineering, McGill University, Montreal QC H3A 0G4, Canada*
[2]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA,*
[3]*Inst. of Engineering, Universidad Nacional Autónoma de México UNAM, Cd. Universitaria, 04510 Mexico City, Mexico*
[4]*Ericsson, Pisa 56124, Italy*
[5]*Ericsson, Saint-Laurent, Montreal, QC H4S 0B6, Canada*
[*]*Santiago.Bernal@mail.mcgill.ca*

Abstract: We report the first O-band coherent transmission using a comb laser and a silicon photonics modulator. We achieved greater than 8.5 Tbps using 19 lines over 10km at 56 Gbaud DP-32QAM. © 2024 The Author(s)

1. Introduction

The demand for faster and more efficient internet speeds is growing exponentially with new data-hungry services such as cloud-based computing, streaming, and AI-driven services. These demands are spurring advancements in data center interconnects (DCI) which are currently being met by intensity modulation direct-detection (IMDD) systems. Meeting increasing demands employing IMDD systems requires wavelength division multiplexing (WDM) technology with high spectral efficiency.

C-band optical comb laser sources have been used in several coherent transmission system-based multi-Tbps demonstrations [1-4] as both the carrier and the LO [5]. Optical comb laser sources are an important WDM transceiver technology, and they have been demonstrated using Kerr micro-resonators [6], electro-optic modulators [7], or quantum-dot (or dash) mode-locked lasers (QD-MLL) [8, 9]. QD-MLLs emit high-frequency pulses with a fixed spacing determined by their cavity length. They are compact, efficient, and robust and do not require initiation routines or feedback loops [10]. They can be integrated with silicon photonics (SiP) and benefit from a high power per line as compared to other optical combs, making them a viable option for scalable WDM systems. Previous C-band demonstrations required digital chromatic dispersion compensation. Additionally, because of their dense laser line spacing (e.g., 28.4 GHz [4]) low symbol rates were typically employed resulting in a high number of components needed to reach multi-Tbps data rates. Alternatively, O-band operation eliminates the need for CD compensation and relaxes laser linewidth requirements thus enabling the use of DFB lasers as opposed to external cavity lasers (ECLs) as the LO over reaches of 10 km [11].

In this paper, we report the first O-band coherent optical fiber transmission system employing a QD-MLL as the carrier and a SiP modulator to transmit net 8.5 Tbps. This was achieved using 19 comb lines each operating at 56 Gbaud DP-32QAM under the 25% overhead soft-decision forward error correction (SD-FEC) threshold. DFB lasers were implemented as the LO to achieve 10 km reach. Finally, we also quantify the system performance as a function of LO type using DFB and ECL LOs.

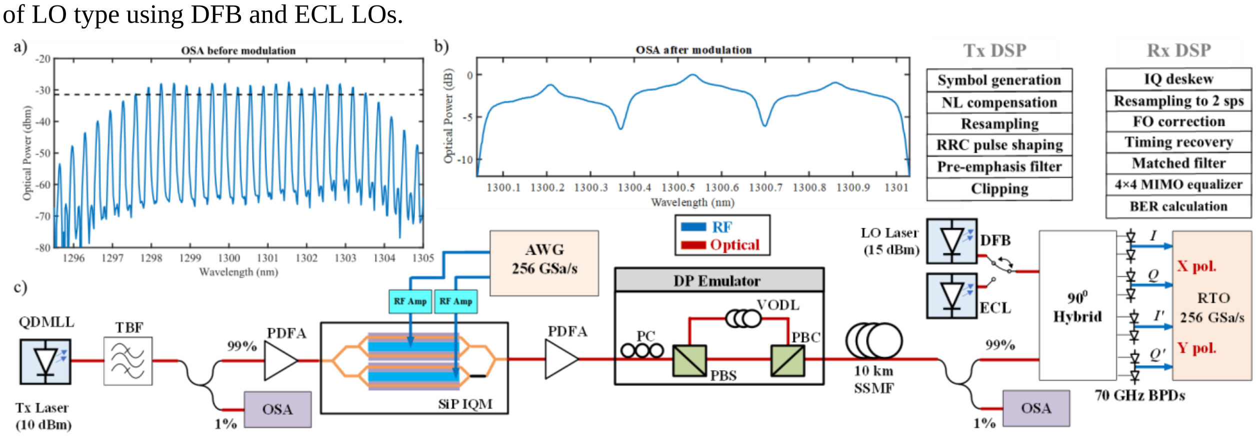

Fig. 1: (a) Optical spectra of the QD-MLL comb and (b) signal spectrum of 3 bulk modulated comb lines at 56 Gbaud DP-32QAM. (c) The experimental setup used for the transmitter (Tx) and receiver (Rx) and the DSP stacks used for each.

2. Experimental setup and DSP stacks

Fig. 1c shows the experimental system. The transmitter (Tx) source consisted of a QD-MLL connected to an O-band Santec OTF-350 optical tuneable bandpass filter (TBF) with a bandwidth range of 0.1 to 15 nm and allowing the testing of any number of comb lines individually or collectively. The pulses were then amplified by a 26 dB praseodymium-doped fiber amplifier (PDFA) to increase the power per line thus compensating for the 5 dB insertion loss (IL) of the TBF.

At the transmitter, we use a Keysight M8199B arbitrary waveform generator (AWG) with two 256 GSa/s digital-to-analog (DAC) channels. First, a random sequence of QAM symbols is generated. The signal is then shaped using a root raised cosine (RRC) filter at two samples per symbol (sps) and resampled to match the rate of the AWG. Multi-line experiments use a RRC roll-off factor of 0.02 to respect the separation between the adjacent comb lines. Next, we pre-compensate the frequency response of the AWG and the RF cables using a digital pre-emphasis filter. The signal is then clipped to limit its peak-to-average power ratio (PAPR) to 9 dB at 56 Gbaud.

We use a 67 GHz GS-SG RF probe and two 38 GHz SHF 806E RF amplifiers to drive a SiP IQ modulator (IQM). The IQM is a single polarization Mach-Zehnder modulator with a fiber-to-fiber insertion loss of 6.3 dB with an additional 9.5 dB from the grating couplers [12]. The SiP IQM has a V_π of 5.8V and 3dB bandwidth of ~30 GHz. The output is then amplified by a PDFA to compensate for not using transimpedance amplifiers at the receiver. We then employ a dual-polarization (DP) emulator by using a polarization controller (PC) and a polarization beam-splitter (PBS) which split the power into two orthogonal polarizations. One polarization is then delayed by 9.2 ns using a variable optical delay line (VODL) to decorrelate the symbols on each polarization. Finally, the signal is transmitted over 10 km of standard single-mode fiber (SSMF).

At the receiver (Rx), we use an O-band DP optical hybrid whose output is connected to four 70 GHz balanced photodiodes (BPDs) and finally to the RTO. The LO consists of either a tunable ECL or an array of DFBs. The ECL and DFBs both had an output power of 15 dBm, a linewidth of ~ 500 kHz and 1 MHz, and a side-mode suppression ratio (SMSR) of 45 and 50 dB, respectively. The DSP at the receiver is performed offline and consists of first deskewing the received signals for each polarization, correcting the frequency offset, and RRC filtering the signal to 2 sps. Then, we employ a 4x4 multiple-input-multiple-output (MIMO) equalizer with real coefficients, interleaved with a first-order phase-locked loop for carrier phase recovery. Finally, the symbols are converted into a bit sequence to calculate the BER.

3. Bulk Transmission using DFBs and ECL LO

The QD-MLL was characterized to optimize the transmission performance by changing the driving current, the saturation absorber (SA) bias voltage, and the temperature. Fig. 2 shows the linewidth, SMSR and number of lines within 3dB attainable by varying the comb state at a constant temperature of 40°C. Increasing the SA bias increased the number of lines within 3 dB of the max line, but it decreased the maximum power per line. This could be mitigated by increasing the driving current. The temperature primarily affected the central wavelength. The spacing of the lines was determined by the cavity length and was fixed at 58.3 GHz. More details of the QD-MLL are found in [10]. The center wavelength was set at 1300 nm and consisted of a ~200 kHz linewidth, a SMSR of 35 dB, and 19 lines within 3 dB by operating the comb at 160 mA, 1.0 V, and 42°C.

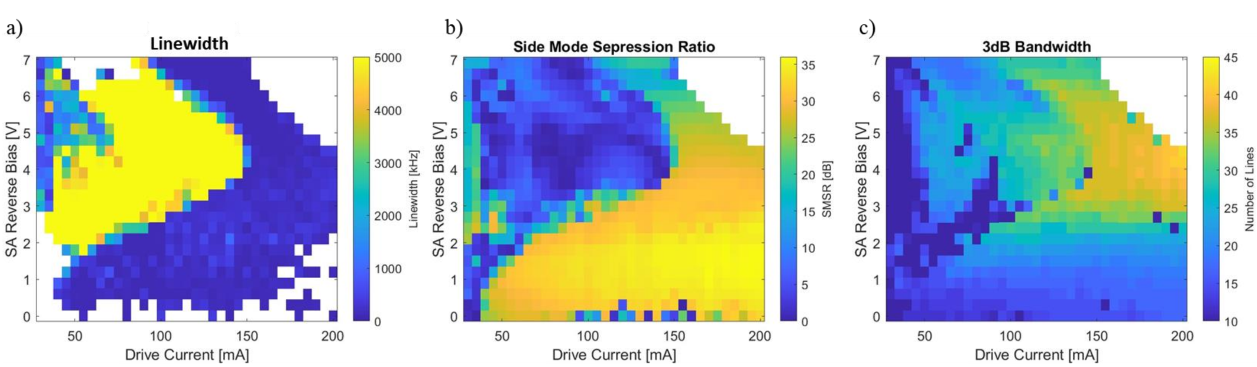

Fig. 2: Different comb states characterizing the (a) linewidth, (b) SMSR, and (c) the number of lines within 3dB of the highest-powered line for different drive currents and saturation absorbers (SA) bias voltages.

All 19 lines were tested using a sliding window. The bandwidth of the Tx TBF is kept constant such that 3 comb lines are bulk modulated and the central line is optimized to mimic a WDM scenario with one aggressor channel on each side of the channel under test. This allows for not stressing the experimental setup optical power budget. At the receiver, only the LO wavelength is tuned, and no other optical filters are used before the hybrid. The BER of each line is shown in Fig. 3 for the DFB array and the ECL as the LO. We achieved net 4.002 and 7.078 Tbps over 10 km using 19 lines at 56 Gbaud DP-QPSK and DP-16QAM assuming the 6.7% overhead HD-FEC and the 20% SD-FEC, respectively. Additionally, net 8.512 Tbps over 10 km was achieved using 19 lines at 56 Gbaud DP-32QAM under the 25% overhead SD-FEC using either an array of DFBs or an ECL. The BER penalty for employing a higher linewidth DFB laser as opposed to an ECL is less than 1 dB in this case, which supports the potential for coherent O-band comb sources to operate at higher symbol rates, requiring fewer and more cost-effective components to reach multi-Tbps data rates. These results further suggest that a single comb line could also be used as an LO. In that case, only one TEC channel would be required to stabilize both the Tx and LO leading to power consumption savings compared to conventional lasers for parallel data transmission [11].

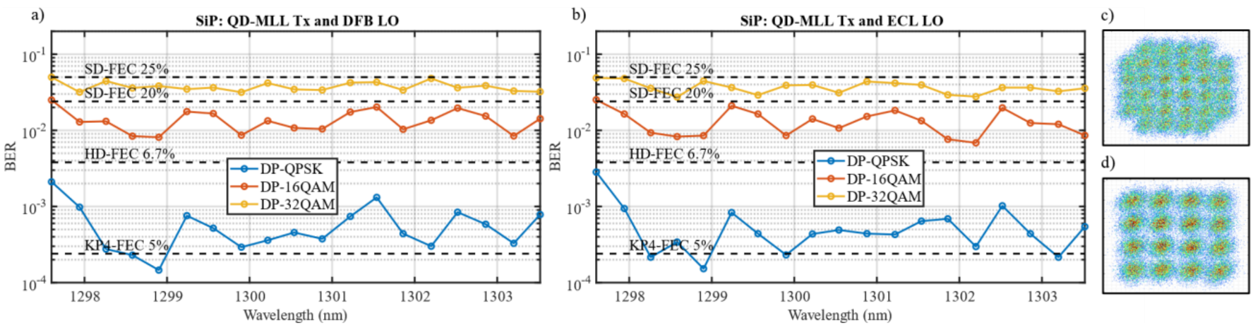

Fig. 3: BER for each line tested using a TBF sliding window employing a) a DFB array and b) an ECL as LO after 10 km. Resulting constellations at 56 Gbaud: c) DP-32QAM and d) DP-16QAM.

3. Conclusion

We presented the first O-band coherent transmission experiment using a SiP modulator and a QD-MLL as the carrier and either a DFB array or an ECL as the LO. The proposed system enables highly parallel data transmission with high throughput, considerable power and complexity reductions, and great integration potential which is attractive for scalable short-reach DCIs.

4. References

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