Integrated Coherent Transmit-Receive Optical Sub-Assembly (IC-TROSA) for 140 GBd Applications

Efthymios Rouvalis, Patrick Domburg, Jörg Honecker, Jens Stephan, Christopher Harbs, Johann Henkel, Ulrich Technau, Andrés Varon, Sebastian Wissig, Georg Clarici, and Matthias Berger

Coherent, Reuchlinstraße 10/11, 10553 Berlin, Germany

efthymios.rouvalis@coherent.com

Abstract: We report on a high output power (>0 dBm), integrated coherent transmit-receive optical sub-assembly (IC-TROSA) integrating all electro-optical and control functions for single-carrier, coherent transmission up to 800 Gb/s. © 2024 The Author(s)

1. Introduction

Building upon the success of the 400ZR/400ZR+ deployments, a new class of coherent 800ZR/800ZR+ pluggable modules is emerging that can deliver net data rates of 800 Gb/s for DCI up to metro network distances [1]. Although no upgrades in spectral efficiency are expected to be realized between these two generations, other very significant factors such as the cost/bit and power consumption/bit become the main driving forces behind 800ZR/800ZR+ implementations. This type of modules require high performance DACs, ADCs and optical components, with typical bandwidths above 60 GHz. However, high bandwidth transceivers combined with low cardinality constellation modes open the door to a much wider range of applications where 400 Gb/s can be offered at a reduced cost without at an even longer reach compared to distances used in previous techno-economic studies [2]. In this paper we report on a high bandwidth IC-TROSA with >0 dBm output power that enables small form factor pluggable transceivers delivering very high bitrate services from Data Center Interconnect (DCI) all the way up to long-reach distances.

2. High Bandwidth IC-TROSA

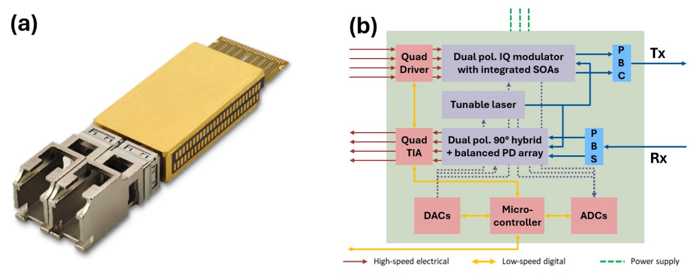

Fig. 1: (a) Image of fully packaged, high bandwidth IC-TROSA, (b) Architectural block diagram of IC-TROSA

Fig. 1(a) illustrates the hermetically-sealed, assembled IC-TROSA package and a high-level block diagram of the internal architecture is shown in Fig. 1(b). Light is generated from a thermally-tuned laser with a linewidth <100 KHz [3] and split into two paths, one towards the Tx and one towards the Rx, acting as the local oscillator (LO). On the transmitter side, highly efficient modulation, amplification, and detection are performed on an InP-based dual IQ-Modulator (IQM) Photonic Integrated Circuit (PIC) with integrated pre- and post-modulation Semiconductor Optical Amplifiers (SOAs), monitor photodiodes. Expanding from our previous work [4], the modulator DC V_π is <1.4 V and the 3-dB electro-optical (E/O) bandwidth is above 60 GHz. On the receiver side, complex signal demultiplexing and detection are performed on an InP-based 90° hybrid with integrated high-speed photodiodes. High bandwidth, four channel driver modulator and TIA ICs amplify the signals from DACs and towards ADCs respectively. Our Type 2 IC-TROSA architecture includes a microcontroller that operates its own firmware and controls all internal functions and communications with the external host using a simple I^2C bus interface [5]. Appropriate high-resolution ADCs and DACs are included in the package to drive and capture DC or low speed signals from the PICs, as directed by the microcontroller firmware. All necessary calibration data are stored in the internal memory of the assembly. The IC-TROSA is fully calibrated over the entire operating frequency range of 5 THz, while with an appropriately modified NLL design it can also support a range of 6 THz, allowing a total capacity for 32 Tb/s for 40×800 Gb/s channels at a channel spacing of 150 GHz.

3. Experimental results

The Tx E/O response of the IC-TROSA was measured up to 67 GHz using a Lightwave Component Analyzer (LCA) with a calibrated, differential RF signal at the input. Large signal compression and saturation effects of the modulator driver were avoided, by setting the input signal power to -20 dBm and the driver gain to the middle of its total range. To extract the actual E/O frequency response of the Tx, the losses from RF cables and PCB traces of the IC-TROSA evaluation board (EVB) were measured using a separate test assembly and subtracted. The results of this measurement with and without EVB losses are shown in Fig 2(a). The IC-TROSA achieved a 3-dB bandwidth in excess of 67 GHz, limited by the maximum operating frequency of the instrument. The Rx opto-electronic (O/E) response was measured using Amplified Spontaneous Emission (ASE) noise from an optical amplifier at the input of the receiver that passed through a tunable optical filter centered at the LO frequency with a bandwidth of 200 GHz. The generated waveforms were captured with a 256 GSa/s Real-Time Oscilloscope (RTO) with a bandwidth of 113 GHz and converted offline into the frequency domain. Fig 2(b) shows the resulting response with and without EVB loss compensation, which were the same as in the Tx case. The 3-dB bandwidth was found to be 67 GHz. For both Tx and Rx, the responses show a peaking between 6-8 dB at about 60 GHz, which can equalize the expected roll-off from the DAC and the ADC in a digital transceiver. We expect that the measured frequency responses can support transmission up to 140 GBd with low implementation penalty. The maximum setting for the peaking magnitude was applied in both cases but it is tunable and can be reduced to equalize the total transceiver Tx and Rx responses.

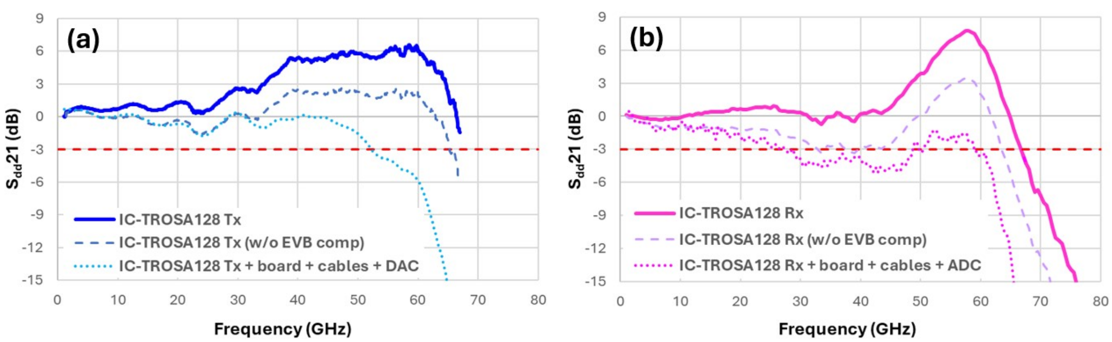

Fig. 2: Measured frequency responses of (a) Transmitter (E/O) and (b) Receiver (O/E) paths of IC-TROSA with compensation for EVB RF losses (continuous lines) and without compensation of EVB losses (dashed lines). Dotted lines illustrate the frequency responses of the Tx and Rx of the overall assembly used for measurements with a real-time DSP EVB, including additional RF losses from cables and the analog frequency responses of the DAC/ADC respectively.

To verify the BER performance at high symbol rates, the IC-TROSA was tested using two separate experimental setups. In the first case, the transmitter signal was generated using an Arbitrary Waveform Generator (AWG) with a 256 GSa/s and an analog 3-dB bandwidth of over 70 GHz (Keysight M8199A). A dual-polarization, 16QAM signal at a symbol rate of 120 GBd was generated that corresponds to a total single channel net rate of 800 Gb/s, assuming a FEC overhead of 20%. Nyquist pulse shaping was applied to the signal out of the AWG to produce a root-raised cosine (RRC)-shaped signal with a roll-off factor of 0.1, which is suitable for transmission with low channel-to-channel crosstalk in a 150 GHz channel spacing. The laser frequency was set to 193.45 THz and the output power out of the IC-TROSA transmitter was set to 0 dBm. The signal was then passed through a noise loading system including a 200 GHz bandpass optical filter. Initially, the received signal was captured using an external 90° hybrid and 4x high speed balanced photodetectors with a 3-dB bandwidth of >70 GHz [6], directly connected to the input ports of a 113 GHz bandwidth Real Time Oscilloscope (RTO) with a sampling rate of 256 GSa/s. In the case of the back-to-back measurement of the IC-TROSA, the 4 outputs of the TIA were connected to the RTO through a break-out printed circuit board (PCB) and long coaxial cables, to match the wide channel-to-channel pitch between the oscilloscope inputs. As in the Tx case, the losses between IC-TROSA and the 1.85mm connectors towards the AWG/RTO added up to 5.5 dB of losses at 60 GHz. After capturing the signals, the waveforms were processed offline with a similar processing sequence as in [7]. Fig. 3(a) shows the results of the BER vs received OSNR. Initially, the IC-TROSA Tx signal was detected using the reference Rx, resulting in pre-FEC BER of 5×10^{-4} at the maximum OSNR (>45 dB) and a Rx OSNR of 25.1 dB at the OFEC threshold (2×10^{-2}). Connecting the IC-TROSA in a back-to-back configuration with an Rx input power of -5 dBm, a Rx OSNR of 26.1 dB at the OFEC threshold and a BER of 1.3×10^{-3} at the maximum OSNR level were measured. We believe that the discrepancy between the two configurations is dominated by the RF losses between IC-TROSA Rx and RTO. Additional experiments at a lower symbol rate of 64 GBd, where RF losses become less critical, showed no difference in required Rx OSNR at a pre-FEC BER of 2×10^{-2} between the two receivers (20.8 dB in both cases).

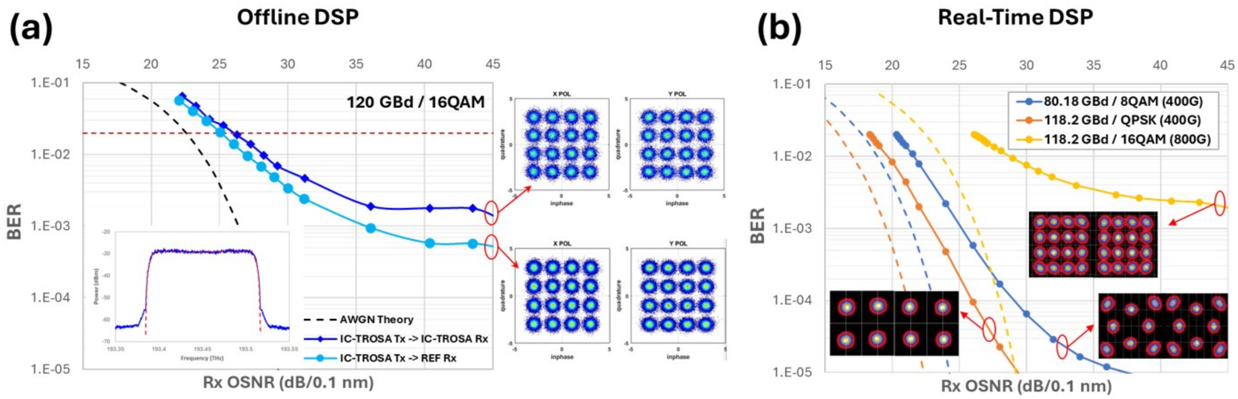

Fig. 3: Experimental results showing: (a) 120 GBd/16QAM BER vs Rx OSNR for IC-TROSA Tx against a reference Rx (light blue circles) and IC-TROSA Rx back-to-back (dark blue diamonds) and offline digital signal processing, (b) BER vs Rx OSNR for back-to-back IC-TROSA for 80.18 GBd/8QAM (400G), 118.2 GBd/QPSK (400G) and 118.2 GBd/16QAM (800G) using a real time DSP ASIC evaluation kit. Dotted lines in both diagrams show the theoretical curves from additive white gaussian noise (AWGN) theory.

In the second case, the IC-TROSA BER against Rx OSNR performance was tested in a back-to-back configuration using a real-time DSP ASIC that was mounted on an EVB. The DSP ASIC EVB was connected to the IC-TROSA EVB using a 16-channel, vertical-mount, on-board connector breaking out to 16 coaxial, length-matched RF cables with a 1.85 mm connector. This transition resulted in additional losses and the resulting E/O and O/E spectra and illustrated in Fig. 2(a) and 2(b) respectively. To measure the overall Tx E/O response of the setup, a flat-top signal was generated from the DSP and was loaded to the DAC without applying any additional pre-distortion. The optical spectrum was captured using a high-resolution optical spectrum analyzer (OSA). For the Rx O/E spectrum we applied the same method as in section 2 but this time the time domain waveforms were captured using the ADC of the DSP ASIC and processed accordingly offline.

The DSP ASIC supports several modes and the IC-TROSA was tested at 3 different combinations of symbol rates and modulation formats: a) 80.18 GBd and 8QAM (400 Gb/s), b) 118.2 GBd and QPSK (400 Gb/s) and c) 118.2 GBd and 16QAM (800 Gb/s). The over-sampling rates of the DAC and the ADC were set to 9/8 and 3/2 respectively. The modulated Tx signal was set to 0 dBm out of the IC-TROSA and was passed through a noise loading system that consisted of EDFAs, VOAs and a tunable optical filter. The Rx input power was set to -5 dBm for all measurements. Fig 3(b) shows the results of the measured BER against the received OSNR. The BER was reported directly from the DSP and error free operation after forward error correction was confirmed for all measurement points. At the OFEC threshold of 2×10^{-2}, the measured Rx OSNR levels for 80.18 GBd/8QAM, 118.2 GBd/QPSK and 118.2 GBd/16QAM were 20.3 dB, 18.3 dB and 26 dB respectively. Once IC-TROSA and DSP ASIC are integrated in a coherent pluggable module through a very short, on-board RF interconnect with a typical length of a few millimeters, we anticipate a substantial improvement in signal integrity. Therefore, a significant reduction in the required Rx OSNR and error floor can be achieved, especially for 16QAM applications.

4. Conclusions

We demonstrated a fully calibrated, high-bandwidth IC-TROSA suitable for 800 Gb/s applications and beyond. A low power consumption in conjunction with a very high level of packaging density allow this optical engine to be easily integrated in small form factor coherent pluggable modules (QSFP-DD, OSFP, CFP2) and line-cards, operating at symbol rates up to 140 GBd. Despite high RF losses between IC-TROSA and DAC/ADC, the device demonstrated excellent BER performance at symbol rates up to 120 GBd. In future work, we will integrate our IC-TROSA with a DSP ASIC in a QSFP-DD form factor, where RF losses between optics and DSP can be minimized, and we will present BER data from these assemblies.

5. References

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