

Design and Challenges in a 100 Gb/s Hybrid-Integrated Photonic Circuit

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Abstract: Hybrid-integrated, 10×10.7-Gbps WDM transmitters and receivers are built upon DML arrays and APD arrays combined with electronic dispersion compensation. 80-km unamplified transmission is demonstrated with devices 32.5 cm² in size and power dissipation under 17 W.

Introduction

The increasing demand for smaller and lower power consuming transceivers is driving the development of more integrated devices. Hybrid integration offers excellent opportunities to combine sophisticated functionalities in a more compact form by consolidating multiple parts onto fewer substrates, each one optimized for a specific task. This technology is less affected by tradeoffs in device performance, fabrication yield and complexity than for example a full monolithic approach. While packaging may lessen some of the advantages above, the additional flexibility in terms of devices' evolution currently make hybrid integration more appealing than either fully discrete or fully monolithic approaches.

We present an example of 10-channel parallel transmitter and receiver optical sub-assemblies (TOSA & ROSA) with an aggregated capacity of 107 Gbps. They consist of arrays of DFB lasers and avalanche photodiodes (APD) combined with silica arrayed waveguide gratings as multi-demultiplexers. A free-space assembly is also included for wavelength-locking purposes and signal filtering required by the used transmission format. The compact TOSA-ROSA pair delivers a power budget in excess of 22 dB that can support unamplified transmission over 80-km standard single-mode fiber (SSMF). The devices can be used in large, distributed optical interconnects or can be banded or interleaved in even larger networks or network's capacities.

TOSA and ROSA

The hybrid-integrated TOSA comprises four main parts: a ceramic board hosting the laser driver circuitry, a DML bar, an array waveguide grating (AWG) optical multiplexer, and a free-space optics assembly for signal spectral filtering and wavelength locking, as in Fig. 1. A DFB bar with 10 channels nominally spaced by 100 GHz is fabricated on a III-V substrate, which also includes back-facet photodiodes and wavelength tuning heaters for each channel. The bar is flip-

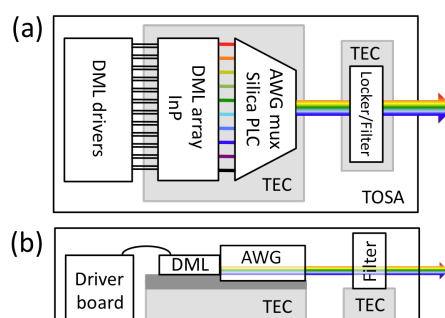


Fig. 1: TOSA's schematic top (a) and side view (b).

chip mounted on a carrier designed to passively, vertically align the lasers to a 1×10 silica AWG multiplexer based on a planar lightwave circuit (PLC) with index contrast of 2%. Lateral coupling adjustments are done actively. The carrier sits on a thermoelectric cooler (TEC) primarily used for AWG's frequency alignment while the lasers' wavelengths are individually tuned by resistive heaters adjacent to each DFB. High density electrical connections to the die was achieved by developing a custom silicon carrier which can accommodate the transition between the larger ceramic design rules and the highly integrated laser array. Additionally, the silicon provides a high thermal conductivity path to the underlying TEC and minimizes expansion mismatches between the DFB array and the AWG.

The multi-wavelength stream is then launched

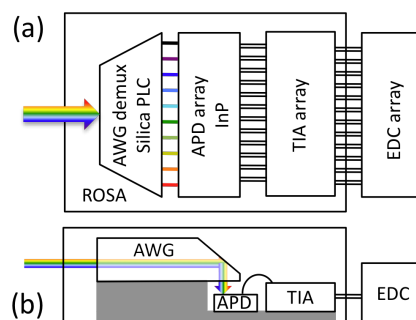


Fig. 2: ROSA's schematic top (a) and side view (b).

into a free-space block comprising collimating lenses, optical isolators, and a Fabry-Pérot etalon with a periodic response matched to the 100-GHz DML's spacing so that all channels can share this single element. The etalon, controlled by another TEC, is used for wavelength locking purposes and to provide the spectral filtering needed to achieve the desired transmission format, as described later. A multi-layer ceramic board contains the control circuitry and the laser driver amplifiers that provide the DC bias and the RF signal currents to the DFBs. Special care is taken in the RF layout to preserve the signal integrity between the differential outputs of the drivers and the single-ended driven DMLs.

Hybrid-integration allows for the minimization of the thermal cross-talk among the different parts and simplifies the heat-sinking of the hot elements. This reduces the TEC's thermal load so that when the AWG's TEC is set to 45 °C the module's power consumption varies from 8.5 to 11.7 W as the case temperature is raised from 10°C to 65°C, respectively.

The ROSA consists of four parts, as shown in Fig. 2. Free-space collimating optics (not shown) feed the incoming stream into a silica AWG demultiplexer that separates the 100-GHz spaced channels. Frequency tuning is achieved via a resistive heater assembled on the same PLC chip. An external turning mirror redirects the light onto an array of APDs. By careful control of the design of the optical path from the AWG facet to the APDs, we achieve high coupling without having to add any intermediate lenses³. A lens array would require increasing the thickness of the ROSA and would complicate the assembly further. The APDs, the linear TIAs and all the passive electronic components are assembled on the base ceramic substrate. Electronic equalization is performed outside the ROSA by commercial low-cost CMOS chips with both feed-forward and decision-feedback equalization (FFE, DFE) capabilities.

Here, hybrid integration allows for the use of low-loss, low-crosstalk, PLC-based demultiplexers combined with high-sensitivity III-V-based APDs. The APD bar shows good uniformity across all diodes with a breakdown voltage of 32 ± 0.5 V and individual dark currents of < 200 nA

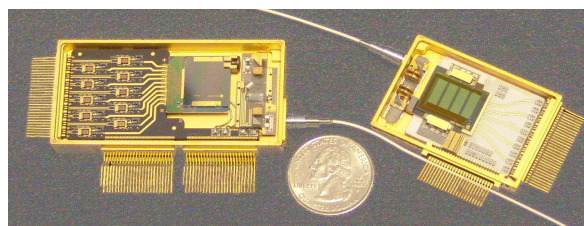


Fig. 3: Photograph of the TOSA (left) and the ROSA (right).

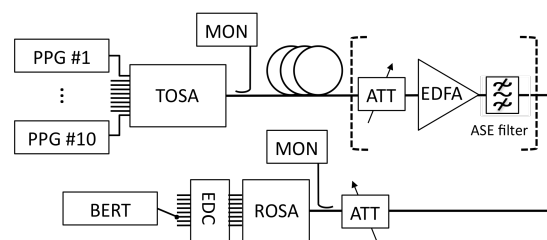


Fig. 4: Schematic experimental set-up. PPG: programmable pattern generator; MON: power and spectral monitor; ATT: variable attenuator; BERT: bit error-rate tester.

with all diodes biased. The per-channel sensitivity of the ROSA is better than -22 dBm at BER of 10^{-12} when tested in back-to-back with 10.7 Gbps XFPGs as reference transmitters. The AWG's operating temperature is targeted above 65°C so that the module's power consumption increases with decreasing case temperature to under 2 W at room temperature in addition to the 4.7 W dissipated by the external EDC chips.

The TOSA and ROSA dimensions are $63 \times 31 \times 9$ mm³ and $43 \times 30 \times 8$ mm³, respectively inclusive of the optical multi- and demultiplexers, the TOSA's DML electrical drivers and the ROSA's TIAs. The package size is limited by the electrical feedthrough density and the relatively complex electrical circuitry rather than by the optical circuits.

Transmission performance

DML-based transmission is strongly affected by the interaction of the laser chirp and the fiber chromatic dispersion. A few options are available to extend the reach such as optical offset filtering⁴, the use of EDC⁵, or a combination of the two^{5,6}. Here, we demonstrate unamplified transmission over 80 km of standard fibers in a multi-channel operation by using an integrated transmitter that includes spectral filtering and an integrated receiver followed by EDC.

When modulated at 10.7 Gbps and driven with an extinction ratio (ER) of 3.5 dB, our DMLs show

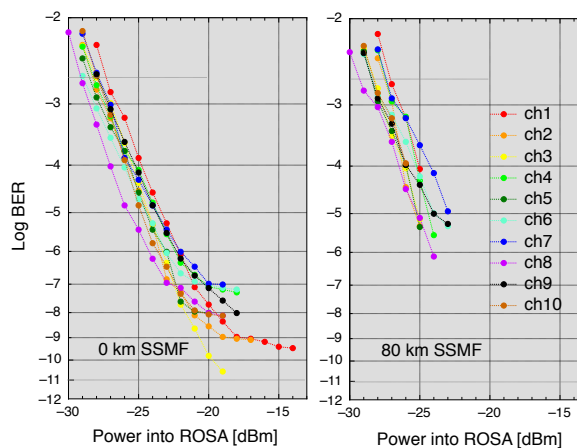


Fig. 5: BER performance vs. received power into the ROSA (before the AWG demux) in B2B and after 80 km of SSMF.

a total positive chirp of between 4 and 5 GHz. A silica Fabry-Pérot filter with a free spectral range of 50 GHz and a finesse of ~ 8 is used in a blue-shifted frequency offset of ~ 2 GHz to increase the output ER to 7-8 dB at the cost of a small extra loss of under 2 dB. Note, these settings are rather different than other chirp-managed lasers (CML) where a smaller input ER and more sophisticated filters must be used⁶.

The BER performance in back-to-back and over 80 km is assessed with the experimental set-up shown in Fig. 4. First, the AWGs in both TOSA and ROSA are aligned to a 100-GHz spaced frequency grid. With DC-bias currents between 65 and 75 mA and proper adjustment of the individual heaters, the TOSA DMLs are brought to the same frequency grid. All lasers are then NRZ modulated at a rate of 10.7 Gbps with a $2^{31}-1$ PRBS sequence supplied by an array of pattern generators. The signals are combined in the AWG and pass through the offset filter in the TOSA. The launched power, measured to be -4.5 ± 1 dBm per channel, is coupled into standard single-mode transmission fiber. A ROSA is used at the link's end for detection and bit error rate evaluation. For a fixed position of the etalon filter, the DMLs' settings are adjusted for best BER performance over 80 km of SSM fiber while maintaining less than 2 dB of power divergence at the input of the link. The curves in Fig. 5 show a consistent performance for all the channels with a spread in sensitivity of ~ 2 dB. Over 80 km it is also shown that sensitivities < -24 and -27 dBm (before the AWG demultiplexer) are achieved at BER of 10^{-4} and 2×10^{-3} , respectively, compatible with typical FEC rates. This corresponds to optical link budgets of ~ 19 and ~ 22 dB. Note that the back-to-back performance is slightly worse than over the longer distance due to the signals' pre-distortion induced on the transmitter side so that the natural positive chirp of the lasers interacts beneficially with the fiber dispersion. The combined electrical and optical cross-talk in multi-channel operation is measured to produce less than 1 dB of penalty and is mostly due to nearest neighbor interactions.

The per-channel BER performances against received optical signal to noise ratio (OSNR) are tested with up to 1500 ps/nm of dispersion by positioning a noise-loading EDFA at the end of the fiber link together with a 12-nm wide, flat ASE filter. Except for the etalon position, the TOSA parameters are retuned for best performance over 80 km and held constant. For input powers into the ROSA of -15 dBm per channel, BER of 10^{-4} and 2×10^{-3} are achieved with OSNR values better than 20 and 15.5 dB, respectively, as shown in Fig. 6. Again, a spread of ~ 2 dB is observed across all channels.

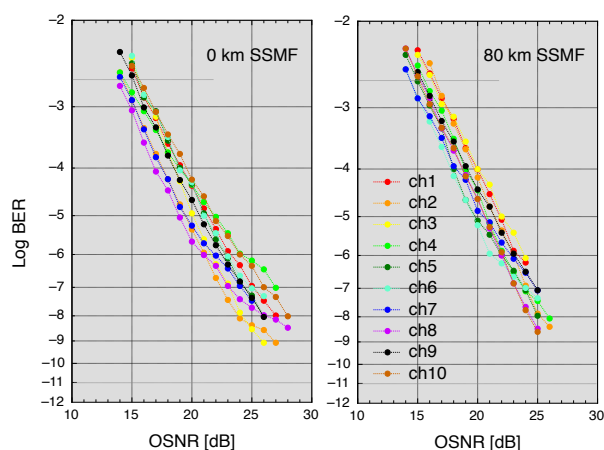


Fig. 6: BER performance vs. received OSNR in B2B and after 80 km of SSMF.

The tolerances with respect to the frequency mismatch between the DML's laser lines and the etalon's position is also verified by thermally tuning the etalon while adjusting the power into the ROSA so to have a BER of 10^{-4} in an 80 km unamplified link. The 1-dB penalty range is found to be ~ 2.5 GHz wide. While such a tolerance may not require a very strict control of the lasers' wavelength like in CMLs, an active feedback is available to prevent long-term drifts.

Conclusions

The hybrid-integration of arrays of DMLs and APDs with PLC-based multi/demultiplexers into 10-channel transmitters and receivers is proven to deliver a power budget sufficient to transmit an aggregated capacity of 107 Gbps over 80 km of unamplified SSMF by using offset spectral filtering at the sources and electronic dispersion compensation at the receiving end. Longer reaches can be bridged if amplification and dispersion management are provided. Compared to commercial XFP transceivers, the proposed TOSA and ROSA have a smaller total size of 32.5 cm^2 and a lower total power consumption under 17 W inclusive of the external EDC chips.

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