High baudrate Silicon Photonics for the Next-generation Optical Communications

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Abstract A silicon photonic integrated coherent transmit & receive optical sub-sssembly with the baudrate beyond 100Gbaud is developed for the next-generation optical communications. Based on this device, 1.06Pb/s transmission over 19-core fiber, 16Tb/s transmission over 10000km G.654E fiber, and 336Tb/s real-time transmission over 332km are demonstrated.

Introduction

Coherent transmission is widely used in optical communications due to its ultra-long reach capacity and high spectral efficiency which is highly beneficial for high capaticy optical transmission systems. However, one challenge hindering the applications of coherent optical transmission is the complexity of the coherent optical transceiver, resulting in high cost and large footprint. Silicon photonics (SiPh) can integrate complex optical functions of coherent optics into a single chip thus minimize the packaging cost and footprint [1,2]. SiPh integrated coherent transmit & receive optical sub-sssembly (IC-TROSA) will find wider and more important applications in future optical communications.

In this paper, we present our recent work on a 100Gbaud SiPh IC-TROSA with ball-grid array (BGA) package technology. Using this high-performance component, we demonstrate beyond 1Pbit/s optical transmission over 19-core fiber, 16Tbit/s Nyquist DP-QPSK transmission over 10000km fiber, and real-time 336Tbit/s DWDM transmission in 7-core fiber over 332km. These three experiments fully verify the potential of our SiPh IC-TROSA in various application scenarios.

Design and fabrication of SiPh coherent transceiver

The SiPh IC-TROSA after package is shown in Fig. 1(a), which consists of a SiPh chip, a driver, and two transimpedance amplifier(TIA) chips. The ball-grid array (BGA) package technology is implemented, see Fig. 1 (b). The four channel driver and dual channel differential TIAs are flip-chip mounted on the substrate. Thermoelectric cooler and hermetic package are not needed. The footprint of the IC-TROSA component is 13mm × 12mm × 3mm and can be mounted on the Printed Circuit Board with surface mount technology (SMT), providing the advantages of low cost, small footprint and high efficiency in module production [3].

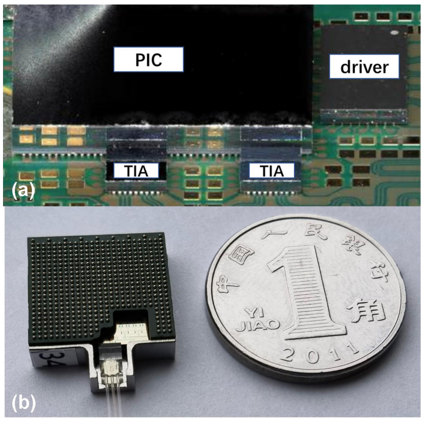

Fig. 1: Photographs (a) inside and (b) outside of the IC-TROSA.

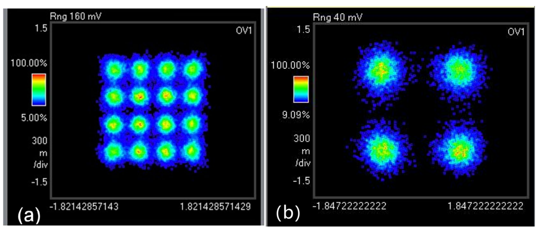

Fig. 2: Constellation diagram of (a) 85GBaud 16-QAM and (b) 100GBaud QPSK.

Inside the IC-TROSA, there is a Si-based photonics integrated circuit (PIC), which was fabricated by the standard commercial-silicon-on

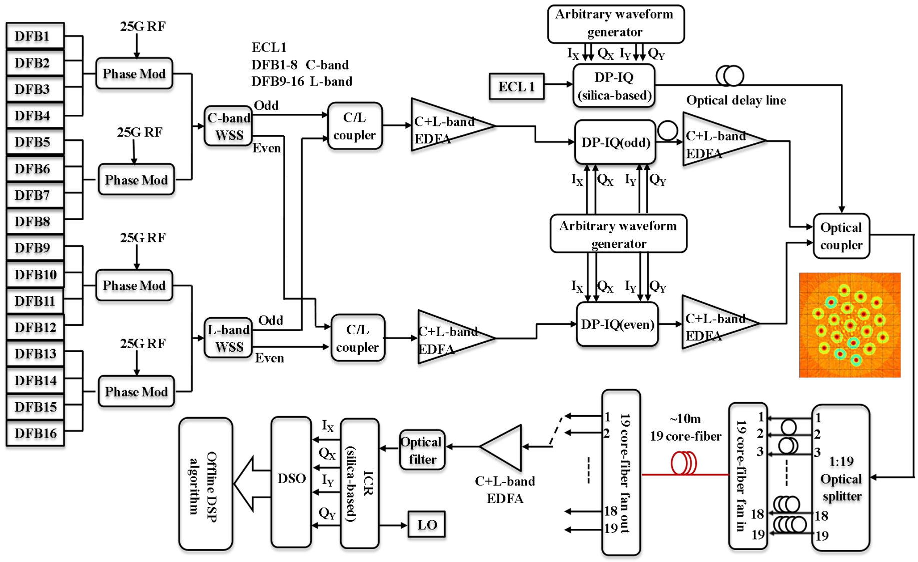

Fig. 3: Experimental set-up for 1.06 Pb/s transmission in a 19-core fiber.

insulator (SOI) wafer with complementary metal -oxide-semiconductor (CMOS) compatible process. The PIC's configuration is similar to that has been introduced in [4]. We integrate 4 MZI modulators [5], 8 high speed photodetectors (PDs) [6,7], 7 optical power monitoring PDs, 6 thermo-optical phase-shifters (TPS) , 14 variable optical attenuators (VOAs), several polarization rotators/splitters [8-10], polarization combiners/splitters, 90° optical hybrid, optical power splitters [11] and optical crossings [12] on a SiPh chip, indicating that all the optics components of a coherent transceiver are monolithically integrated except the laser source.

The 3-dB EO and OE bandwidth of the fully-packaged IC-TROSA is both measured as > 40GHz, both meet the OIF's class 40 criteria. We experiment high-baud-rate coherent signal generation using our SiPh IC-TROSA. A 128Gs/s four-channel arbitrary waveform generator (AWG) is connected to the transmitter and the modulated signal is received by an Optical Modulation Analyzer (OMA) with a 256-GS/s sampling rate. 85GBaud PDM-16QAM and 100GBaud PDM-QPSK constellations are obtained in back-to-back configurations as shown in Fig. 2. The measured BER is 3.04E-3 and 4.78E-4 for 85GBaud PDM-16QAM and 100GBaud PDM-QPSK, which are under the threshold of soft decision forward error correction (SD-FEC). Using this high-baudrate IC-TROSA, we carried out three experiments of optical fiber transmission to verify the application prospect of SiPh in future optical communications.

Ultra-high-capacity optical transmission

First, we demonstrate the optical transmission beyond 1Pbit/s over 19-core single-mode fiber. The experiment setup is shown in Fig. 3.

Sixteen lasers generate 375 optical carriers with 25GHz spacing covering the C+L band. DFTS-OFDM(orthogonal frequency division multiplexing) signal of 149Gb/s net rate is modulated on each optical carrier using the SiPh IC-TROSA. After modulation, the signal is split and amplified in C- or L-band EDFAs before recombination. The combined optical signals are then split into 19 channels and launched into the 19-core fiber via a fan-in device. After transmission, the optical signals are de-multiplexed via another fan-out device. A 0.4nm tunable bandpass filter is used to select the test channel. Signal reception is performed in the receiver part of IC-TROSA. The BER is measured for each core for 375-channels. Fig.6 (b) shows the maximum, minimum and average BER for each channel. The results shown that all channels have BER below a threshold of 2.0E-2, assumed for soft-decision FEC. This translates to a raw transmission capacity of 1.06Pb/s for a 20% coding overhead. The optical spectrum of the 375 channels is also shown in Fig. 4.

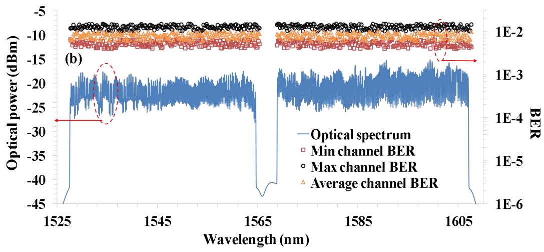

Fig. 4: Max, min and average BER of the 19 spatial channels for the 375 measured wavelengths with optical spectrum.

Ultra-long-haul optical Transmission

Second, we realize a ultra-long haul optical transmission using the SiPh IC-TROSA, G.654E fiber and Raman amplifier [13].

In the experiment, a 50GBaud single-carrier optical Nyquist DP-QPSK signal is transmitted. Total capacity of 16Tb/s has been achieved in the 10000 km fiber link. We further provide the transmission results of 64GBaud single-carrier Nyquist DP-16QAM signal. The experimental results show that 20Tb/s (50λ×400Gb/s) Nyquist DP-16QAM in 50 WDM optical channels with a channel spacing of 75GHz in the C-band are also successfully transmitted over 4000km G.654E fiber. The BER results are shown in Fig. 5.

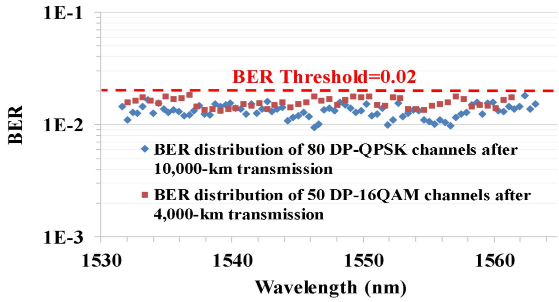

Fig. 5: Measured curve of all the BER of the transmission signals before and after 10000 km and 4000 km transmission.

Real-time optical transmission using CFP2-DCO module

At last, we experimentally evaluate the real-time transmission performance of a seven-core-fiber-based high-capacity system using a SiPh CFP2-DCO transceiver module designed for C+L band operation. The module integrates our SiPh IC-TROSA and a commercial DSP. 336Tbit/s 120-channel DWDM signals are successfully transmitted over 332km with spectral efficiency of 37.3bit/s/Hz. We investigate the performance of CFP2-DCO module at selected wavelength in the optical back-to-back (OBTB) case. Fig. 6 (b) shows the performances of optical signal-to-noise ratio (OSNR) versus BER for the test channel signal. The best application range of this silicon photonics transceiver is around 1550nm, and it only shows a performance loss of less than 1dB in the L-band.

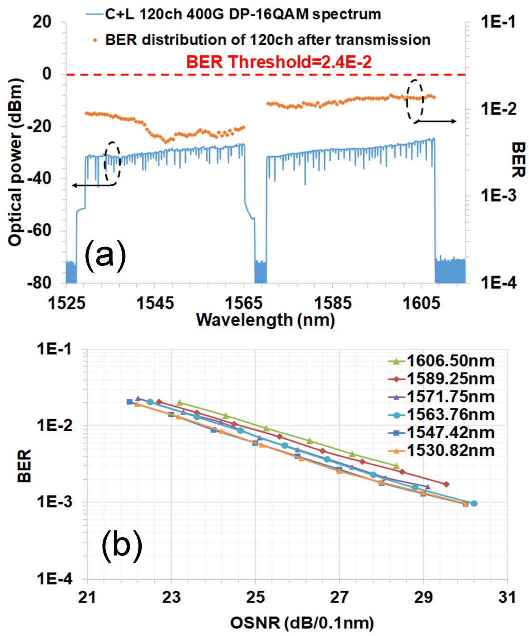

Fig. 6: (a) Transmission performance and spectrum of 120-ch; (b) Back-to-back BER performance at selected wavelength.

Conclusions

Based on our 1.06Pb/s transmission over 19-core fiber, 16Tb/s Nyquist DP-QPSK transmission over 10000km G.654E fiber, and 336Tb/s real-time transmission over 332km are successfully realized. The optical signals are modulated and received by a packaged SiPh IC-TROSA. The experimental results show the potential of SiPh IC-TROSA as a low cost and low complexity solution for ultra-high-capacity, ultra-long-distance and broadband optical transmission.

Acknowledgements

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