Experimental Demonstration of 51.2 Tb/s Self-Homodyne Coherent Interconnects on a 3D Photonic Chip Inspiring Coherent Technology Transfer to Centimeter-Scale Ultra-Short-Reach Applications

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Abstract: We demonstrated a record net 51.2 Tb/s (800Gb/s PDM-64QAM x 64 Channels) ultrafast laser inscribed 3D photonic chip interconnects based on self-homodyne coherent detection, showing the feasibility of coherent technology transfer to ultra-short-reach applications.

1. Introduction

Driven by emerging communication services such as cloud computing, online education, and high-definition video, the data center traffic has been growing explosively. To meet the ever-increasing demand of traffic, coherent detection with higher order modulation and spectral efficiency may be eventually needed in the future [1]. However, traditional intradyne-based coherent detection requires the use of narrow linewidth lasers and complex digital signal processing (DSP) algorithms, which limits its adoption by short-reach optical interconnects. Self-homodyne detection (SHD), on the other hand, has been known to bring much relaxed requirement in terms of component specifications and DSP [2, 3]. So far, SHD has attracted much research attention, 400-Gb/s SHD transmission over 2.3-km single-mode fiber (SMF) [4], 600-Gb/s SHD transmission over 5-km SMF [5], 800-Gb/s SHD transmission over 2-km SMF [6] and 1-km SMF [7] have been reported, and achieved favorable performances. However, 800-Gb/s SHD transmission over 40-km SMF is rarely reported. While industry is currently looking for suitable coherent-lite solutions for data center interconnect (DCI) applications, photonic chip scale coherent transmission may soon become an important research subject. It is generally believed that three-dimensional (3D) photonic chips with higher degree of integration will play important roles in enabling future ultra-high-capacity optical interconnects. In such ultra-short-reach chip-scale applications, cost and power consumption will definitely be even more demanding than today's data center applications such as LR (10km), ZR (40km and 80~120km), and so on. Then questions are, would SHD be suitable for photonic chip level applications at centimeter transmission reach scale? How to develop such a chip-level SHD transceiver?

In this paper, we demonstrate, for the first time, a record net 51.2 Tb/s on-chip optical interconnects based on SHD, using an ultrafast laser inscribed 3D photonic chip. A 3D photonic chip with 64 data channels is fabricated by femtosecond laser direct writing technology, each data channel carrying 800 Gb/s polarization-division multiplexing (PDM) 64-ary quadrature-amplitude modulation (QAM) signals. The experimental results show the prospect and feasibility of coherent technology transfer from long-distance transmission to photonic chip-scale transmission in large-capacity optical interconnects applications.

2. Concept of SHD interconnects on 3D photonic chips

Fig. 1(a) illustrates the concept of SHD transmission, ranging from tens of kilometers SMF to cm-scale 3D photonic chip. The output from the distributed feedback (DFB) laser is split into two separate parts, one of which loads PDM-64QAM signal and the other act as a pilot-tone (PT). The signal and PT are transmitted to a coherent receiver through similar medium which may be fibers or photonic chips. The PT with the same central frequency and reference phase as signals act as LO in the receiver. In this way, the portion of DSP related to carrier frequency offset and carrier phase recovery can be removed, and very expensive lasers with narrow-linewidth and wavelength-locking capabilities are no longer required. Therefore, compared with traditional coherent detection, SHD may have a great potential to achieve high-capacity with lower cost and power consumption in optical interconnects applications ranging from tens of kilometers of SMF to ultra-short-reach centimeter-scale photonic chips.

Fig. 1(d) shows the schematic of femtosecond laser direct writing system. A high repetition rate Ytterbium-based laser (second harmonic generation at 515 nm wavelength, 100 kHz repetition rate, 234 fs pulse duration) is used for femtosecond laser direct writing. A charge-coupled device (CCD) and a light emitting diode (LED) system are employed to monitor the femtosecond laser direct writing process in real time. The femtosecond laser beam is modified by a 300nm linear slit and then vertically focused on a glass sample with a size of 20mmx30mmx1mm by a 50X0.42 objective (M Plan Apo NIR, Mitutoyo). The high peak power of femtosecond laser induces localized nonlinear absorption at a laser focus, resulting in a change in refractive index. As the glass sample moves with the XYZ air-bearing stage, waveguides are formed. The schematic structure of the ultrafast laser inscribed 3D photonic chip is displayed in Fig. 1(c). The 3D photonic chip contains a total of 68 single-mode waveguides, distributed in four layers. The first and third layers are distributed along the east-to-west direction, and the second and forth layers are distributed along the north-to-south direction. The spacing between each layer of the 3D photonic chip is 30 μm, and each layer contains 17 single mode waveguides with a pitch of 127 μm. In each layer of the 3D photonic chip, signals are transmitted through 16 waveguides and PT is transmitted through the 17th waveguide.

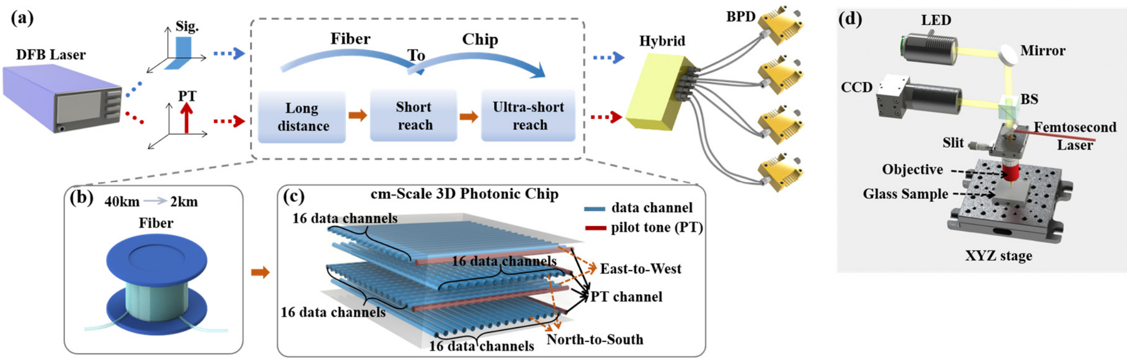

Fig. 1. (a) The concept of proposed SHD transmission, ranging from tens of kilometer SMF to cm-scale 3D photonic chip; (b) The schematic of fiber; (c) The schematic structure of the ultrafast laser inscribed 3D photonic chip; (d) The schematic of femtosecond laser direct writing system.

3. Experimental setup

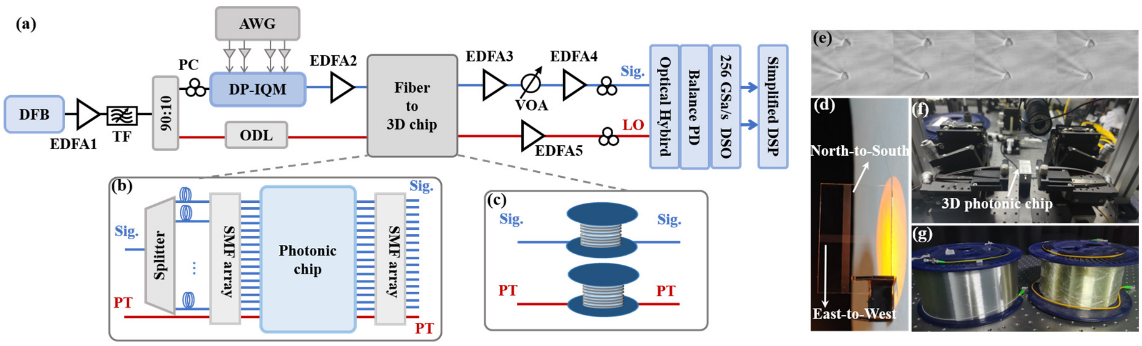

Fig. 2. (a) Experimental setup of SHD interconnects on 3D photonic chips and SHD transmission over km-scale SMF; (b) Experimental setup of SHD transmission on 3D photonic chips; (c) Experimental setup of SHD transmission over SMF; (d) Photo of the 3D photonic chip; (e) Partial cross section of the 3D photonic chip; (f) Photo of chip coupling platform; (g) Photo of SMF.

Fig. 2(a) illustrates the experimental setup of SHD interconnects on 3D photonic chips and SHD transmission over km-scale SMF. At the transmitter, the output at a wavelength of 1550nm from a DFB laser with a linewidth of 1MHz is pre-amplified by an erbium-doped fiber amplifier (EDFA) and then a tunable filter is used to reduce the amount of amplified spontaneous emission noise. Then it is divided into two separate channels by a 90:10 coupler, one of which acts as PT and the other channel is modulated. 80-Gbaud PDM-64QAM sequences are pre-distorted to compensate the nonlinearity of I/Q modulator (IQM) and loaded into an arbitrary waveform generator (AWG, Keysight M8199A) at a sampling rate of 120GSa/s. Four SHF S804B RF amplifiers with 60-GHz bandwidth drive the RF signals to a dual-polarization IQM with 35-GHz bandwidth. For the system of SHD transmission over 3D photonic chips, the corresponding experimental setup is shown in Fig. 2(b), where the signal carriers are spilt into 16 channels with different relative delays for data decorrelation. The 16 sets of signals and PT are coupled into the 3D photonic chip by an SMF array. The signals and PT transmitted through the first 16 waveguides and 17th waveguide, respectively. Then the signals and PT are coupled to another SMF array. Fig. 2(d), (f) display the photos of photonic chip and photonic chip coupling platform, respectively. The partial cross section of the 3D photonic chip is shown in Fig. 2(e). For the system of SHD transmission over km-scale SMF, a pair of SMF are used to transmit signals and PT, respectively. Fig. 2(g) shows the photo of SMF. At the receiver, a state-of-the-art 2x8 optical 90°-hybrid and four 70-

GHz balanced photodiodes (BPDs) are used. A real-time sampling oscilloscope (Keysight UXR0594A) operating at 256 GSa/s digitizes the electrical signal. The receiver DSP only consists of resampling and real-value 4x4 MIMO equalization.

4. Experimental results and discussions

The performance of SHD transmission ranging from 40-km SMF to 2-km SMF and finally to 3D photonic chips is characterized. At first, the bit-error rate (BER) performance of 800Gb/s PDM-64QAM in 40km SMF and 2km SMF versus the received optical signal-to-noise ratio (OSNR) is measured, as shown in Fig. 3(a) [8]. For 40-km SMF, the receiver DSP additionally adopts chromatic dispersion compensation algorithm. Then we characterize the performance of net 51.2Tb/s (800Gb/s PDM-64QAM x 64 Channels) SHD optical interconnects over the centimeter-scale 3D photonic chip. Fig. 3(c)-(f) depict measured BER performance of one channel of the waveguides in each layer, respectively. Compared with the performance at back-to-back (BTB), the measured OSNR penalty at a BER of 1.25×10^{-2} (assuming the use of CFEC threshold as for 400ZR) is about 1.2 dB. Fig. 3(b) shows the measured BER performance of 64 signal channels of the 3D photonic chip at an OSNR of 38dB. The measured BERs on all channels are below 1.25×10^{-2} and the similar BER performance is achieved for all channels, indicating that femtosecond laser inscribed 3D photonic chip possesses favorable characteristics well suited for high-capacity SHD transmission.

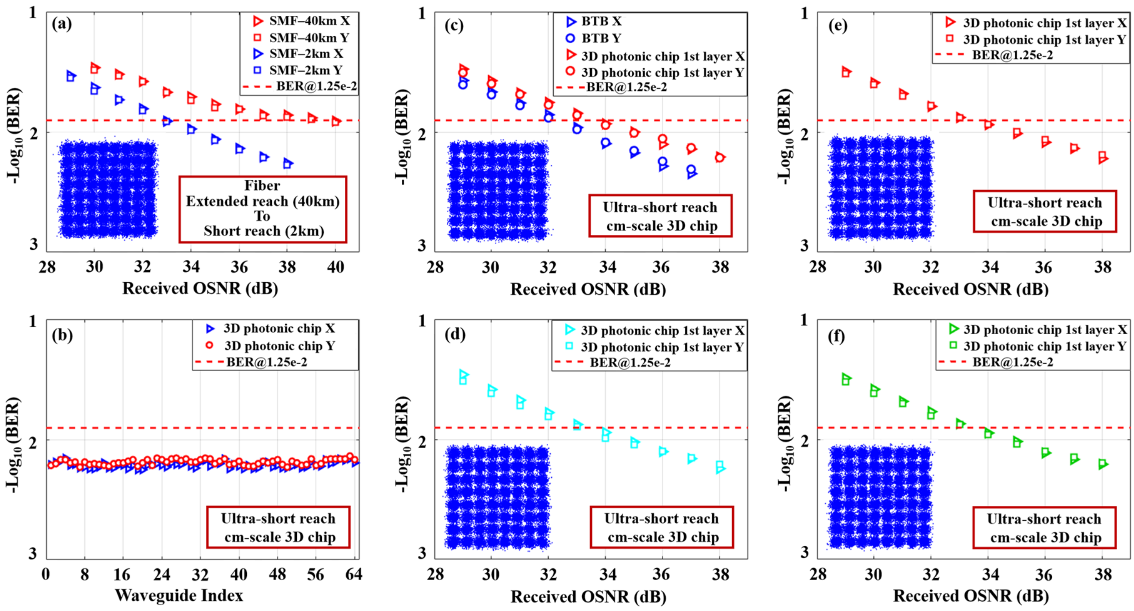

Fig. 3. (a) The measured BER performance versus the received OSNR for 40-km SMF and 2-km SMF; (b) The measured BER performance of 64 signal channels of the 3D photonic chip at an OSNR of 38dB. The measured BER performance of one waveguide channel of the chip in (c) 1st layer; (d) 2nd layer; (e) 3rd layer; (f) 4th layer. The inserts are the constellations of 800Gb/s PDM-64QAM.

5. Conclusion

In summary, we have demonstrated a record net 51.2 Tb/s SHD interconnects on an ultrafast laser inscribed centimeter-scale 3D photonic chip. There are totally 64 data channels and 4 PT channels on the 3D photonic chip, each data channel transmitting 800Gb/s PDM-64QAM signals. We have also verified the SHD transmission over 40-km SMF and 2-km SMF. Such favorable performances indicate that SHD transmission on 3D photonic chips may have great potential for future high-capacity ultra-short reach optical interconnects.

6. Acknowledgements

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7. References

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