19-Core SDM Self-Homodyne Coherent Transmission using Fan-In/Fan-Out Photonic Lantern

Min Yang[1], Chengkun Cai[1], Yize Liang[1], Lei Shen[2], Yanjun Zhu[3], Hua Zhang[4], Chaonan Yao[4], Yuchen Shao[4], Lei Zhang[2], Changkun Yan[2], Liubo Yang[2], Ruichun Wang[2], Jun Chu[2], Jian Wang[1*]

[1] *Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China.*

[2] *State Key Laboratory of Optical Fiber and Cable Manufacture Technology, YOFC, Optics Valley Laboratory, Wuhan, Hubei, China.*

[3] *Hisence Broadband Inc, 2580 North First Street, San Jose, CA 95131, USA.*

[4] *Hisence Broadband Multimedia Technologies Co., Ltd, No.399 Songling Road, Qingdao, China.*

**Corresponding author: jwang@hust.edu.cn*

Abstract: We experimentally demonstrate space-division multiplexing (SDM) self-homodyne coherent transmission in 19-core fiber with low-cost, MHz-linewidth distributed feedback (DFB) laser, using fan-in/fan-out (FIFO) photonic lantern based on femtosecond laser direct writing technique. © 2023 The Author(s)

1. Introduction

The access network rate of end-customers and data traffic of short-reach optical interconnection has been growing explosively, driven by emerging communication services such as cloud computing, online education, and high-definition video. With the increasing demand for high-capacity optical communication systems, technological advances such as wavelength-division multiplexing, polarization-division multiplexing, space-division multiplexing (SDM), and multi-level modulation formats with coherent detection assisted by digital signal processing (DSP) have been explored. Remarkably, the SDM using multi-core fibers (MCFs) has been considered a promising approach for overcoming transmission capacity limitation of both long-haul transmission and short-reach transmission systems [1, 2]. Self-homodyne detection SHD has the property of cancelling the laser phase noise by using a pilot-tone (PT) light as the local oscillator (LO) transmitted through one SDM channel [3], offering the benefits of low power consumption and low cost for SDM systems. In SDM-SHD systems, the transmitted PT can be shared with all the remaining signal channels, and thus the reduction in spectral efficiency with PT transmission is inversely proportional to the number of SDM channels.

A fan-in/fan-out (FIFO) device for MCFs that couples each core with individual single-mode fiber is one of necessary components for an MCF-based SDM transmission. There are several types of FIFO devices have been proposed for MCFs including fiber bundle type [4], fuse fiber type [5], free space type [6] and integrated chips [7]. Among these types, an on-chip FIFO waveguide based on femtosecond laser direct writing has attracted much attention recently due to its capability to map from an arbitrary two-dimensional arrangement to a linear array. The femtosecond laser inscribing photonic lanterns in glass chips appears to be one of the most competitive schemes.

In this paper, using low-loss and low-crosstalk FIFO photonic lantern based on the femtosecond laser direct writing technique, we demonstrate the implementation of SDM-SHD transmission in 19-core fiber with low-cost and MHz-linewidth distributed feedback (DFB) laser. One channel of 19-core transmits PT and the remainders are used for data signals. Each data channel of 19-core fiber carries 22-GBaud dual-polarization (DP) 64-quadrature-amplitude modulation (QAM) signals.

2. SHD configuration with FIFO Photonic Lantern

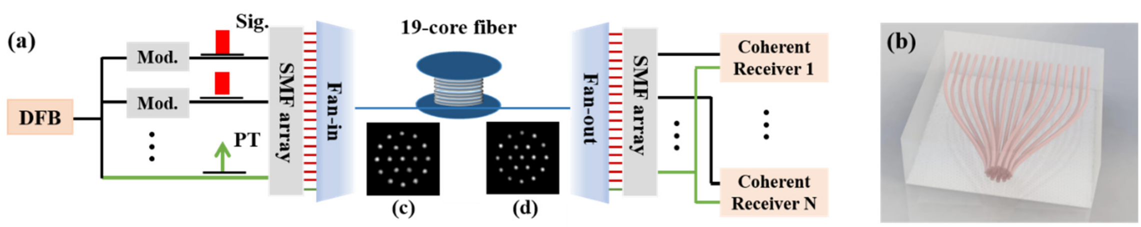

Fig. 1. (a) The proposed 19-channel SDM-SHD configuration using FIFO photonic lanterns in glass chips based on femtosecond laser direct writing technique; (b) Concept of the femtosecond laser inscribed photonic lantern in a glass chip; (c) the intensity profile of output light field of the photonic lantern; (d) the intensity profile of output light field of 19-core fiber.

Fig. 1 illustrates the proposed 19-channel SDM-SHD configuration using FIFO photonic lanterns in glass chips based on femtosecond laser direct writing. The carrier from the laser is split into 19 separate spatial channels with one channel transmitting PT and the remainder carrying the signal. Then the 18 sets of signals and PT are coupled into the fan-in photonic lantern device by an SMF array. After 19-core fiber transmission, the signals together with PT are coupled output to another SMF array via the fan-out photonic lantern. The entire coupling process is monitored by a visible CCD to achieve accurate coupling alignment. Finally, the transmitted signals and PT are injected into a coherent receiver to obtain the electrical signals. The transmitted LO, as the transmitted signal, has the same central frequency and reference phase. This approach can minimize the impact of laser phase noise and omit the frequency offset. Therefore, in the SDM-SHD system, there is no longer required the expensive laser with narrow-linewidth and wavelength-locking capabilities that is essential in intradyne detection systems.

Fig. 1(b) shows the concept of the femtosecond laser-inscribed photonic lantern in a glass chip with a size of 40mm*20mm*1mm. The femtosecond laser inscribing is performed at a wavelength of 515 nm with a repetition rate of 200 kHz. The 19 linear array beams transmit along distinguished waveguide trajectories in the photonic lantern, and the end of 19 waveguides are mapped into the two-dimensional arrangement which matches the core distribution of the 19-core fiber. The intensity profile of output light field of the photonic lantern is captured by a CCD, as shown in the Fig. 1 (c). One can clearly see the uniform intensity distribution of the 19-core. Fig. 1(d) shows the output intensity profile after 1-km 19-core fiber transmission, indicating that the output light field is accurately coupled to the 19-core fiber. The measured insertion losses and inter-core crosstalk of the 19-channel of the photonic lantern are all less than 1.5dB and 35dB, respectively.

3. Experimental setup

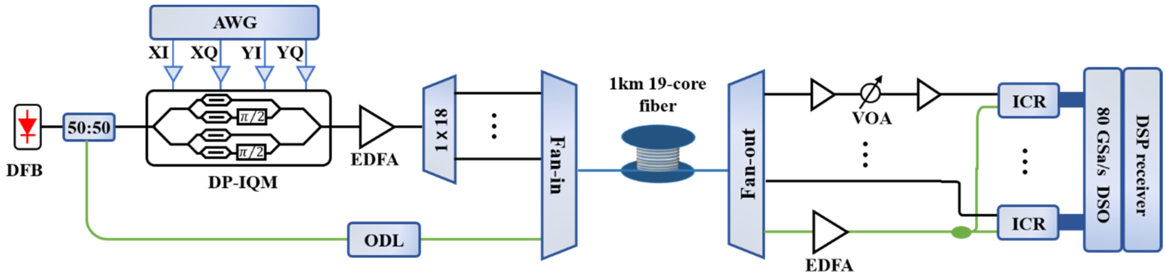

Fig. 2. Experimental setup of 19-channel SDM-SHD system. DFB: distributed feedback laser. EDFA: erbium-doped fiber amplifier. AWG: arbitrary waveform generator. DP-IQM: dual-polarization IQ modulator. ICR: integrated coherent receiver. VOA: variable optical attenuator. DSP: digital signal processing.

Fig. 2 illustrates the experimental setup of 19-channel SDM-SHD system. At the transmitter, the carrier from the DFB laser with a linewidth of 1MHz is split into two separate fibers by a 50:50 coupler, one of which transmits PT and the other are modulated by 22-Gbaud DP-64QAM RF signals produced by an arbitrary waveform generator (AWG, Tektronix AWG70002). The signal carriers are divided into 18 channels with different relative delays for data pattern decorrelation. Then the signals and PT are injected into the FIFO system consisting of two photonic lanterns and 1 km 19-core fiber. At the receiver, the remote LO is split into 18 parts to achieve coherent detection of the 18 signals. The erbium-doped fiber amplifier (EDFA) in PT path is used to compensate for the link loss. A real-time sampling oscilloscope (Keysight DSA-Z 204A) operating at 80 GS/s stores the detected signal for offline processing. To enable SHD, it is vital for the accurate alignment of path length between signal and PT. Minn synchronization algorithm at receiver DSP and an initial calibration-purpose-only IQ modulator are applied to realize the path length matching between signal and LO. After aligning the path length, the calibration-purpose-only IQ modulator is removed. The LO, output from the same laser as the signal, has a similar optical transmission path to the signal transmission path in the SDM-SHD system. The transmitted LO, as the transmitted signal, has the same central frequency and reference phase, minimizing the impact of laser phase noise and omitting the frequency offset. Therefore, complex carrier recovery algorithm is no longer needed in receiver DSP, which can reduce the complexity and power consumption of DSP.

4. Experimental results and discussions

The performance of 19-channel SDM-SHD system is characterized. At first, the bit-error rate (BER) performance versus the received optical signal-to-noise ratio (OSNR) for several spatial channels (Ch.7, Ch.17, Ch.8, Ch.9, Ch.13) is measured, as shown in Fig. 3(a) and 3(b). To reduce the impact of inter-core crosstalk, the outer core (Ch.16) with fewer neighboring cores is chosen for remote LO transmission. The measured OSNR penalty at a BER of 1.5 $\times 10^{-2}$

(20% hard-decision forward-error correction (HD-FEC) threshold) among these channels is less than 0.5dB. Fig. 3(c) depicts the measured BER performance of 18 signal channels at an OSNR of 22dB, the insert shows the defined core number of 19-core fiber. The measured BERs on all cores are below1.5 $\times 10^{-2}$ and the similar BER performance indicates that femtosecond laser inscribed photonic lanterns possess favorable characteristics for 19-channel FIFO. Fig. 3(d) shows the constellations of 22-Gbaud DP-64QAM of Ch.7 and Ch.15 at an OSNR of 23dB.

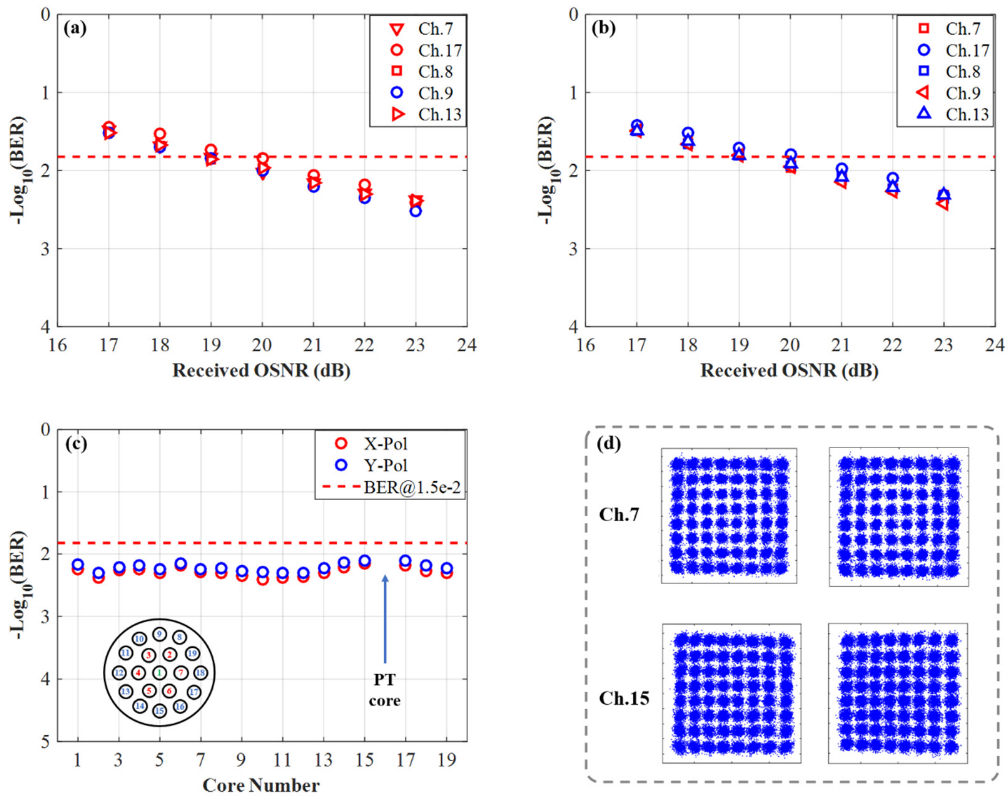

Fig. 3. The performance of 19-channel SDM-SHD system using FIFO photonic lanterns. The measured BER performance versus the received OSNR for several spatial channels on (a) X-polarization; (b) Y-polarization. (c) The measured BER performance on all cores of 19-core fiber at an OSNR of 22dB. (d) the constellations of 22-Gbaud DP-64QAM of Ch.7 and Ch.15 at an OSNR of 23dB

5. Conclusion

In summary, by exploiting low-loss and low-crosstalk femtosecond laser inscribed FIFO photonic lantern, we experimentally demonstrate the implementation of 22-Gbaud DP-64QAM SDM-SHD transmission with low-cost DFB laser with a linewidth of 1MHz. The signals are loaded on 18 channels of 19-core fiber, where one of the outer core acts as PT channel and all signal channels show similar BER performance. The achieved favorable performance indicates that 19-channel SDM-SHD system with photonic lanterns can effectively scale the transmission capacity and reduce the system cost.

6. Acknowledgements

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