Experimental Demonstration of Single-wavelength net 16.1Tb/s Self-Homodyne Coherent Transmission over a 24-Core Fiber

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Abstract: We demonstrate the transmission of 102-Gbaud DP-16QAM signals over a 2.7km 24-core fiber in the SDM-SHD system, employing MHz-linewidth DFB laser and FIFO devices based on femtosecond laser direct writing technique. © 2024 The Author(s)

1. Introduction

In recent years, the exponential growth of data services has promoted the extensive exploration of space division multiplexing (SDM) [1]. Adopting multi-core fibers (MCFs) in SDM systems can not only increase the information carrying capacity of single optical fiber but also reduce energy consumption and improve efficiency via integrated optical hardware [2]. Self-homodyne detection (SHD), using one channel to transmit pilot-tone (PT) light as the local oscillator (LO), is an effective technique to eliminate the impact of laser phase noise. The requirements for digital signal processing (DSP) and narrow linewidth lasers can be greatly relaxed in SHD system [3]. Therefore, the utilization of SHD technology in SDM systems based on single-mode MCFs (SM-MCFs) is regarded as meaningful exploration to improve the communication capacity and reduce the cost of the optical networks [4]. It is worth noting that in order to transmit multiplexing signals independently in different cores of SM-MCF, a fan-in/fan-out (FIFO) device is necessary to achieve accurate coupling between SM-MCF and single-mode fibers. Some FIFO devices have been developed for MCFs, such as fuse fiber type [5], free space type [6] and integrated chip [7] and so on. Among them, the FIFO devices fabricated by femtosecond lasers on transparent materials are considered as one of promising schemes due to their low connection loss, low cost and high flexibility.

In this paper, we experimentally demonstrate self-homodyne transmission of a 2.7km 24-core fiber carrying 102-Gbaud dual polarization (DP) 16-quadrature amplitude modulation (QAM) signal per data channel using the on-chip FIFO device based on femtosecond laser direct writing technique. 23 channels of 24-core SM-MCF are used to transmit signals and the remaining core is for PT. The gross data rate of single channel has reached 816 Gbit/s so that the total data throughput has reached 18.7 Tbit/s. Assuming that the pre-forward-error correction (pre-FEC) threshold has 15% overhead, the single channel net data rate and total net data rate are 700 Gbit/s and 16.1 Tbit/s, respectively.

2. Concept and principle of SDM-SHD system with FIFO device

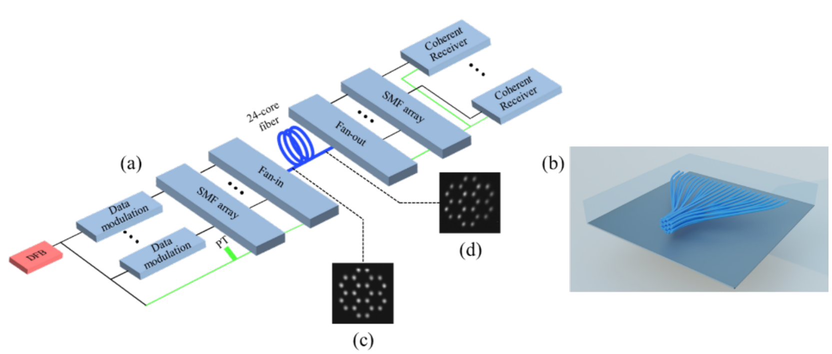

Fig. 1. (a) Conceptual illustration of SDM-SHD system of a 2.7km 24-core SM-MCF; (b) Concept of the femtosecond laser inscribed on-chip FIFO device; (c) the output light field intensity profile of FIFO device; (d) the output light field intensity profile of 24-core SM-MCF.

The concept and principle of SDM-SHD transmission system assisted by the fabricated FIFO device is illustrated in Figure 1(a). A low-cost MHz-linewidth distributed feedback (DFB) laser is employed as the source to generate the

carrier for transmitting signals and PT. The single-channel signal carrier is divided into 23 independent channels. A SMF array is employed to accurately couple the 23 independent data channels and one PT channel into the FI device under a visible CCD monitoring. As the transmission of 24 carriers in the fiber is completed simultaneously, 24 independent channels are obtained after the opposite operation to the front end. A Coherent receiver performs coherent detection on the local oscillator waveform and each other signal waveform. Since the remote LO and the signal light go through the similar optical link, they have the same central frequency and reference phase, which can greatly reduce the impact of laser phase noise and ignore the frequency offset. Accordingly, the low-cost DFB lasers can be used to replace the relatively expensive narrow-linewidth external cavity lasers (ECLs) in the SDM-SHD system.
The schematic diagram of the 24-channel FIFO device fabricated in a glass chip through femtosecond laser inscribing technique is displayed in the Figure 2 (b). Under the real-time monitoring of the LED lighting system, the FIFO device is inscribed by a femtosecond laser beam with repetition rate of 100 KHz, wavelength of 515nm and pulse duration of 234 fs. The 24 waveguides originally arranged horizontally in sequence are rearranged at the end of the FIFO device into a two-dimensional arrangement that highly matches the core distribution of the 24-core SM-MCF. Figure 2(c) shows the output light field intensity profile after 24 beams passing through the FIFO device. Figure 2(d) shows the intensity profile of all beams after coupling and transmission. It can be seen that the output light field intensity of each core is almost weakened in the same extent, which indicates that the core distribution at the end of the FIFO device has been accurately matched with the 24-core SM-MCF.

3. System configuration

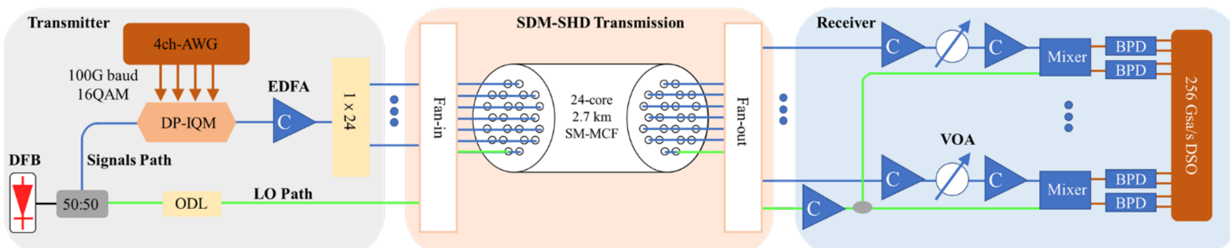

Fig. 2. Experimental configuration of transmitting 102-Gbaud DP-16QAM signals over a 24-core SM-MCF in the SDM-SHD system. ODL: Optical delay line. DP-IQM: dual-polarization IQ modulator. AWG: arbitrary waveform generator. EDFA: erbium-doped fiber amplifier. VOA: arbitrary waveform generator.

The experimental configuration of the SDM-SHD system is shown in Figure 2. A 50:50 coupler at the transmitting end is used to divide the optical carrier generated by the 1MHz linewidth DFB laser into two identical parts. The DP-IQM modulates the 102-Gbaud DP-16QAM signals from an AWG onto one of the two optical carriers. After being amplified by an EDFA, the SDM signals are separated into 23 different SMF output ports with the aid of a SMF array, each of which has different relative delays for data pattern decorrelation. Another optical carrier carrying PT is directly coupled into the FI device together with the 23 signal beams, and coupled to the corresponding 24-core SM-MCF. All optical carriers are transmitted in the 2.7km SM-MCF and then reversely received by the FO device with the same structure, and coupled to the single-mode optical fiber, respectively. The optical carriers of 23 signals are attenuated and amplified, and then coherently detected with the LO waveform, respectively. It should be noted that the PT path only contains EDFA and ODL, where EDFA is employed to compensate the loss of LO transmission link, and ODL is used to achieve the length alignment between the signal path and PT path required by the SHD system. This operation is achieved by adding an IQM behind the transmitter source and adopting the Minn synchronization algorithm at the receiver. SHD can be implemented through simply removing the IQM when the length of two paths are precisely aligned. The introduction of SHD eliminates the requirement for complex carrier recovery algorithms in the DSP at the receiver, thereby reducing DSP complexity and power consumption.

4. Results and discussions

At first, we select the outer core (Ch. 1) with fewer adjacent cores among the 24 cores to transmit PT, which can reduce the impact of crosstalk between cores. Secondly, five cores (Ch. 4, Ch. 9, Ch. 11, Ch. 18, Ch .24) of the other 23 transmitted signals are chosen according to distance to represent all cores to characterize the performance of the SDM-SHD system. Figures 3(a)-(e) display the measurement results of the relationship between the bit-error rate (BER) performance and the received optical signal-to-noise ratio (OSNR) of two polarizations of the five selected channels, respectively. The inserts show 102-Gbaud DP-16QAM constellations for measured channels at an OSNR of 35dB. The OSNR penalty among different channels is basically less than 1dB near the BER threshold of

$1.25x10^{-2}$ (taking the concatenated forward error correction (CFEC) threshold of 400 Ze Best Range (ZR) as a reference), which indicates that the crosstalk between different cores is at a low level during the process of transmission. Figure 3(c) depicts the measured BER performance of each signal channels at the OSNR of 35dB. The insert in Figure 3(f) shows the core number of 24-core SM-MCF we defined. The measured BER on all spatial channels for transmitting signals can reach the level of below $1.25x10^{-2}$, which further demonstrates the favorable performance of high-capacity SDM-SHD fiber transmission.

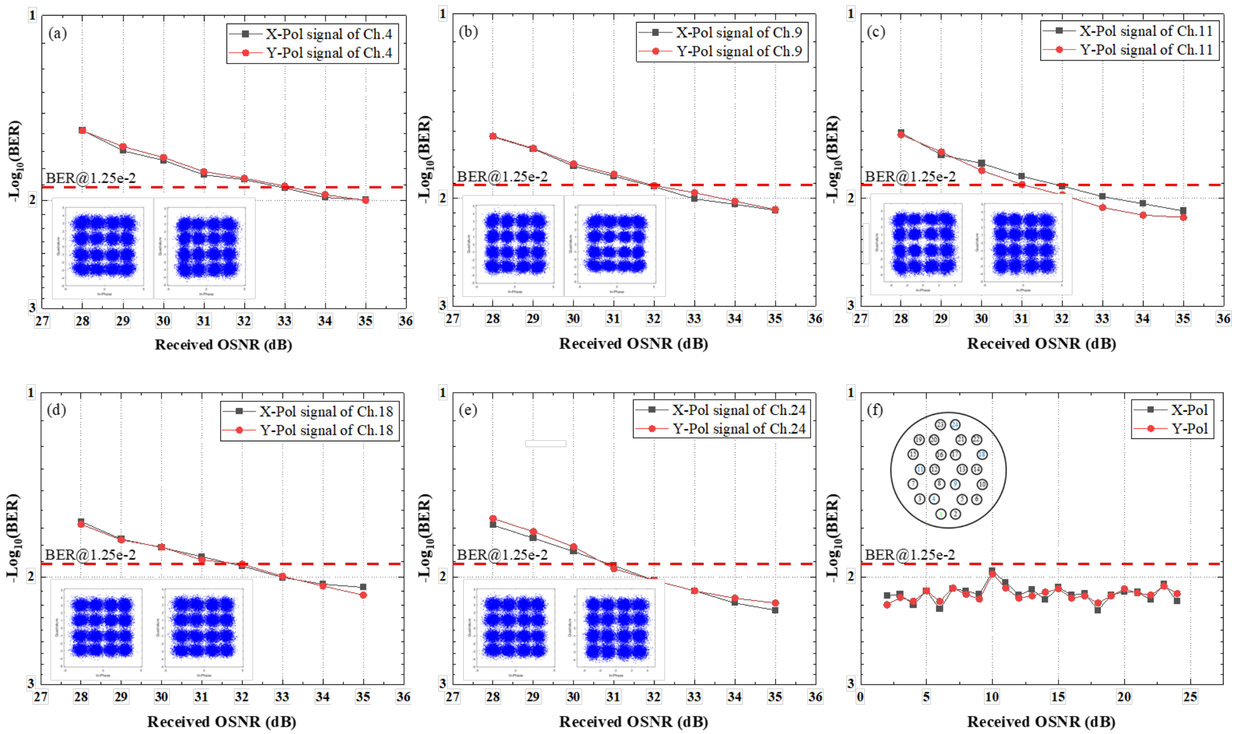

Fig. 3. The performance of 24-channel SDM-SHD system. The measured BER performance versus the received OSNR of two polarizations for (a) Ch. 4; (b) Ch. 9; (c) Ch. 11; (d) Ch.18 (e) Ch. 24; (f) The BER performance on all cores of 24-core SM-MCF at the OSNR of 35dB

5. Conclusion

To sum up, we have demonstrated that the optical carrier generated by a 1MHz-linewidth DFB laser carries the 102-Gbaud DP-16QAM signals over a 2.7km SM-MCF through exploiting SHD technique and femtosecond laser inscribed on-chip FIFO devices in the SDM-SHD system. The single channel net data rate of 700 Gbit/s and total net data rate of 16.1 Tbit/s are achieved, respectively. The favorable experimental results suggest that the MCF-based SDM-SHD system possesses the ability to achieve ultra-high-capacity and provides an alternative solution for expanding the communication capacity of the system.

6. Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) (62125503, 62261160388), the Natural Science Foundation of Hubei Province of China (2023AFA028), the Innovation Project of Optics Valley Laboratory (OVL2021BG004), and the Cooperation Project between Hisense Broadband and Huazhong University of Science and Technology.

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