130.6-Tb/s Self-homodyne Coherent Transmission over Weakly-Coupled FMF for Data Center Applications

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Abstract: We experimentally demonstrate high-capacity MDM self-homodyne coherent transmission over 30-km weakly-coupled 10-mode fiber with specially designed multiple-ring-core profile, achieving a total throughput of 130.6 Tb/s with 9 information-bearing modes carrying 16-λ 120-GBaud PCS 64-QAM signals.

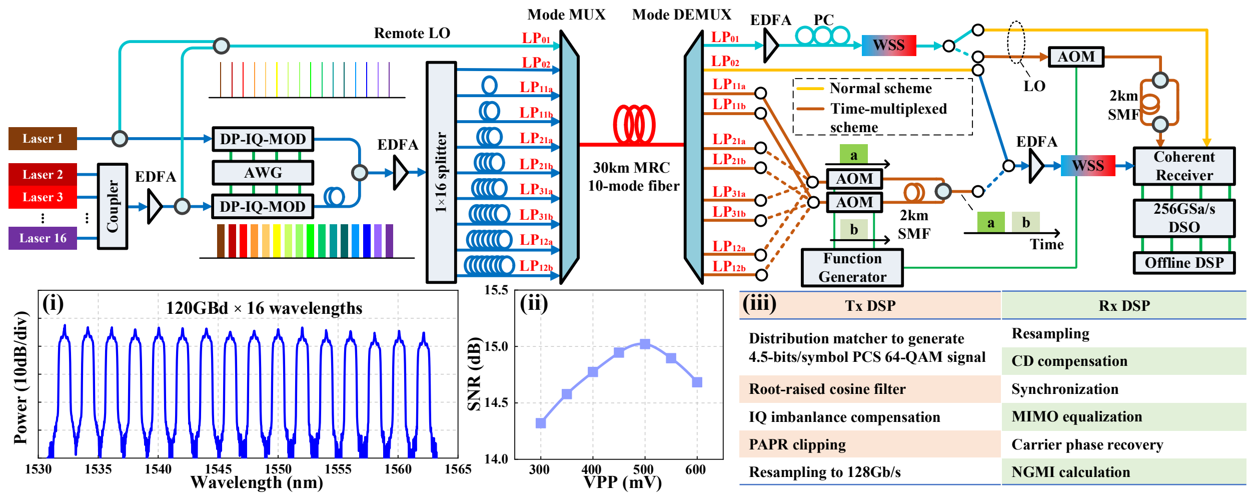
1. Introduction

As hyper-scale data centers and cloud computing continue to expand, the demand for network bandwidth has been growing exponentially. Over the next 5-10 years, electrical switches inside data centers are expected to support 51.2-Tb/s switch or higher [1]. Self-homodyne coherent detection (SHCD) technology has been proposed as a cost-effective candidate for high-speed optical interconnections, which eliminates the need for high-stable lasers of transceivers and simplifies required digital signal processing (DSP) [2]. However, with various advanced transmission techniques, the transmission systems based on single-mode fiber (SMF) are approaching their capacity crunch. Mode-division multiplexing (MDM) schemes based on few-mode fibers (FMF) have evolved rapidly for their potential to enhance the transmission capacity of a fiber core by orders of magnitude [3]. In addition, FMF with 125-um cladding benefits from using current existing cabling technologies and avoiding technical problems such as mechanical reliability, coupling/splicing tolerance, and production yield [4]. Weakly-coupled MDM SHCD is an attractive scheme, in which signals and a remote local oscillator (LO) originating from the same laser can be transmitted independently in separate mode channels to eliminate the need for another separate fiber or fiber core [5]. Considering the usage of 800-Gb/s coherent interface and coarse wavelength division multiplexing (WDM), the single-fiber capacity in MDM-SHCD systems with over 130 mode/wavelength channels is expected to reach over 100 Tb/s. However, the transmission capacity of MDM-SHCD demonstration has been limited so far due to undesirable interference between channels [5-7]. To enable high-capacity MDM-SHCD transmission, weakly-coupled MDM links with low modal crosstalk for transmission FMFs, mode multiplexers/demultiplexers (MUX/DEMUX), and their connection are required.

In this work, we demonstrate a high-capacity self-homodyne transmission over 30-km specially designed multiple-ring-core (MRC) 10-mode fiber. The architecture has four main benefits: (1) Both wavelength and space dimensions are exploited to significantly scale the available channels, offering a three-orders-of-magnitude increase in capacity; (2) Multiple rings of index perturbations in the FMF core are applied to achieve ultralow modal crosstalk, which provides the potential for the weakly-coupled MDM transmission with a large number of spatial modes; (3) Remote LOs are delivered in one of the mode channels for self-homodyne coherent reception, eliminating the need for another LO-delivering fiber/core and simplify the system implementation complexity; (4) 125-um standard cladding FMF allows high productivity, superior mechanical reliability and low manufacturing costs. Here, we achieve a net rate of 130.6Tb/s (8.16Tb/s/λ) with 9×16 MDM/WDM channels carrying 120-GBaud probabilistic constellation-shaped (PCS) 64-quadrature-amplitude modulation (QAM) signals. This work unlocks the potential of MDM-SHCD systems for ultra-high-capacity intra/inter-data center optical interconnects.

2. Experimental setup

The experimental setup for MDM-SHCD transmission over weakly-coupled 10-mode FMF is illustrated in Fig. 1. At the transmitter side, optical carriers are split into two separate paths for remote LO and signal modulation, respectively. For the test band, the optical carrier is generated by a tunable external-cavity laser. Nyquist-shaped PCS 64-QAM (4.5-bits/symbol entropy) baseband signal with a roll-off factor of 0.01 is generated by an arbitrary waveform generator (AWG) operating at 128-GSa/s, which drives a dual-polarization optical in-phase and quadrature modulator (DP-IQ-MOD) to generate a 120-GBaud optical signal. Another 15 tunable external-cavity lasers followed by an optical coupler, an erbium-doped fiber amplifier (EDFA), a modulator, and a 25-ns optical delay are used to generate the WDM dummy channels, which are driven by the AWG negative outputs. The two rails are then combined to obtain a 16-channel WDM signal over the C-band (1531.3~1562.9 nm) with 250-GHz channel spacing. All WDM channels are measured in turns by sequentially tuning the test-band laser to the corresponding wavelength and the dummy channels are also tuned to be adjacent. The measured optical spectrum of the WDM signals is presented in inset (i) of Fig. 1. The output swing of the AWG is swept and optimized to be 500 mV in this experiment, as shown in inset (ii) of Fig. 1. The generated signal is amplified by an EDFA and equally split by an optical coupler for the 9 spatial modes, which are de-correlated with an adjacent optical delay difference of 150 ns. Then, the remote LO and the signals are coupled into and out of the 30-km weakly-coupled 10-mode fiber through the mode MUX and DEMUX.



(iii) Tx DSP	Rx DSP
Distribution matcher to generate 4.5-bits/symbol PCS 64-QAM signal	Resampling
	CD compensation
Root-raised cosine filter	Synchronization
IQ imbalance compensation	MIMO equalization
PAPR clipping	Carrier phase recovery
Resampling to 128Gb/s	NGMI calculation

Fig. 1 Experimental setup for the high-capacity MDM-SHCD transmission. Inset (i) Measured optical spectrum of the transmitted WDM signal. (ii) Back-to-back (BtB) signal SNR versus AWG output swing. (iii) DSP algorithms employed for transmitter and receiver. SNR: signal-to-noise ratio; PAPR: peak-to-average-power ratio; CD: chromatic dispersion.

At the receiver side, the remote LO is amplified by an EDFA and filtered by wavelength-selective switches (WSS) for selecting the LO in accordance with the center wavelength of the test band. To deal with the polarization wandering of the remotely delivered LO, an optical polarization controller (PC) is used to emulate the adaptive/automatic PC [8]. A time domain multiplexed (TDM) receiver scheme is adopted for the reception of degenerate LP_{mn} (m>0) modes, in which the optical signals from $LP_{mn,\,a}$ and $LP_{mn,b}$ modes are temporally separated with a 2-km SMF delay and then combined to occupy orthogonal time slots, while the same delay is also applied to the LO for phase matching. Three acoustic-optic modulators (AOM) driven by a function generator source are used to achieve sequential control. Finally, the received electrical signals are sampled by a real-time digital storage oscilloscope (DSO) operating at 256 GSa/s for performing offline DSP, as illustrated in inset (iii) of Fig. 1. The samples were processed by adaptive 2×2 MIMO equalizer for the non-degenerate LP_{0n} modes or 4×4 MIMO equalizer for degenerate LP_{mn} modes.

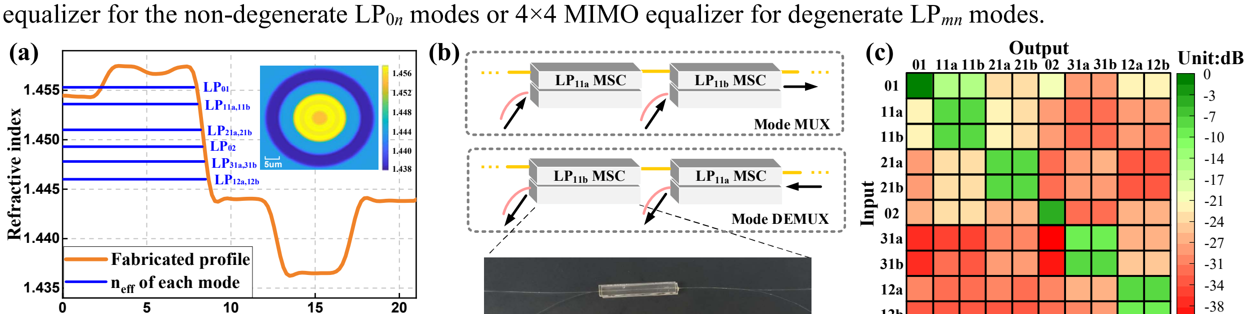


Fig. 2 (a) Index profile of the fabricated MRC FMF, as well as the effective index of each guided mode. (b) Cascaded structure diagram of the mode MUX/DEMUX. (c) Normalized crosstalk matrix at 1550 nm.

Figure 2(a) presents the index profile of the fabricated weakly-coupled MRC FMF supporting 10 modes (6 LP modes). In the proposed core structure, rings of index perturbations are utilized to separate the n_{eff} and enlarge the A_{eff} of all LP modes as much as possible. For the fabricated FMF, the min|Δn_{eff}| is 1.54×10^{-3} lying between LP_{02} and LP_{31} modes, guaranteeing the weak coupling among the 6 LP modes [9]. The mode effective areas A_{eff} of all 6 LP modes are larger than 125-um^2, which means the FMF has less nonlinear transmission impairment under high-power or long-span transmission conditions. Fig. 2(b) shows the diagram of the matched mode MUX/DEMUX consisting of cascaded all-fiber mode-selective couplers (MSC). The MSCs are fabricated by side polishing and mating process to reduce the insertion loss and modal crosstalk [10]. The maximum BtB insertion loss and modal crosstalk for the pair of mode MUX/DEMUX are 5.8 and -15 dB, respectively. Fig. 2(c) shows the normalized crosstalk matrix of 30-km FMF with a pair of MUX/DEMUX at 1550 nm, in which the maximum crosstalk is -14.2 dB between LP_{01} and LP_{11}. Thus, LP_{01} mode with high power is reserved for transmitting the remote LO in this experiment to avoid transmission impairment originating from LP_{01-11} signal crosstalk.

3. Results and discussion

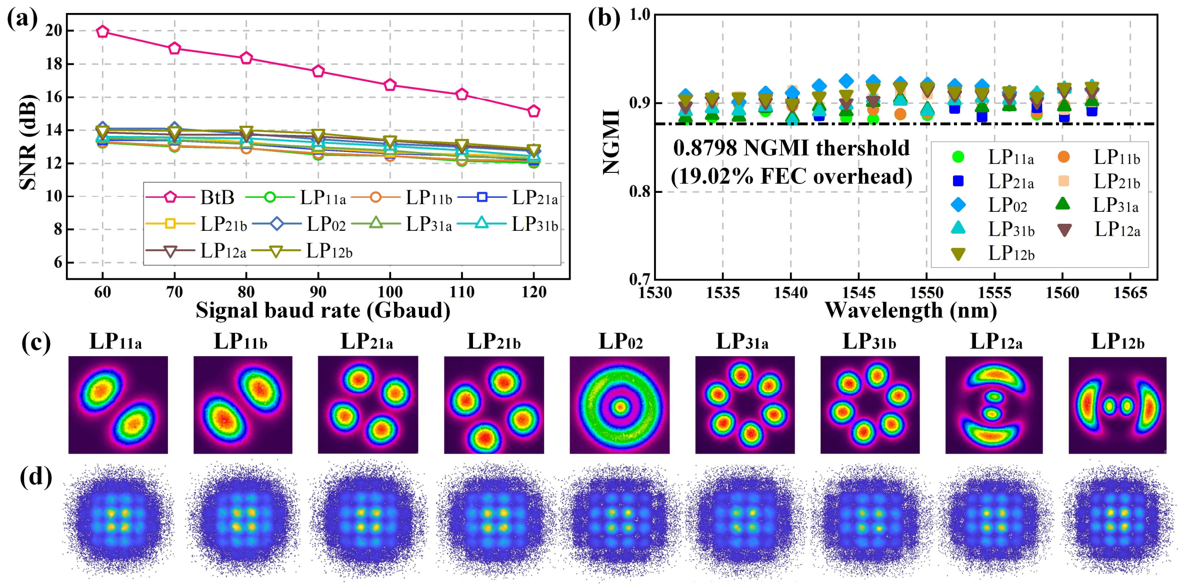


Fig. 3 Performance of the MDM-SHCD system. (a) Measured SNR versus baud rate of signal. (b) NGMI performance of 120-Gbaud PCS-64-QAM signals in the 9 mode channels at 16 wavelengths. (c) Mode patterns at 1550 nm after 30-km FMF transmission. (d) Recovered PCS-64QAM constellations of the 9 mode channels at 1550-nm wavelength.

The performance of the proposed MDM-SHCD system is characterized in Fig. 3. The SNR performance versus the baud rate of signal is swept for both BtB and the 9 information-bearing spatial channels after 30-km MDM transmission, as shown in Fig. 3(a). The SNR gap of about 3-4 dB between the MDM transmission and BtB curves mainly results from the unsuppressed modal crosstalk in the link, which is also manifested by the crosstalk matrix in Fig. 2(c). Modal crosstalk appears to be insensitive to the baud rate, resulting in only small performance changes with variations in the baud rate. Therefore, the proposed system has the maximum transmission capacity when the bandwidth of the signal reaches the limit of the transceiver. With the 120-Gbaud PCS-64-QAM signal, the normalized generalized mutual information (NGMI) performance of 9×16 channels is demonstrated, as shown in Fig. 3(b). The measured mode patterns and constellations of the 9 mode channels at 1550 nm are shown in Fig. 3(c) and (d), respectively. The LP_{02} and LP_{12} modes exhibit better performance with the former avoiding TDM receiver loss and the latter suffering lower modal crosstalk. All the NGMI are higher than a practical NGMI threshold of 0.8798 using 19.02% forward error correction (FEC) overhead [11]. Excluding the 19.02% FEC overhead, the achieved net rate is 130.6 Tb/s (8.16 Tb/s/λ) in this experiment. This represents the highest achieved throughput of MDM self-homodyne coherent transmission.

4. Conclusion

In summary, we have demonstrated an MDM self-homodyne coherent transmission employing a weakly-coupled 10-mode MRC fiber and matched mode MUX/DEMUX. A total net rate of 130.6Tb/s has been achieved with 9×16 MDM and WDM channels. The results highlight the potential of MDM-SHCD systems for ultra-high-capacity data center applications.

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5. References

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