Single-Core 7.2-Tb/s (800-Gb/s×9) MDM Self-Homodyne Coherent Transmission over Weakly-Coupled 10-Mode Fibre

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Abstract *We propose a mode-division-multiplexing (MDM) self-homodyne coherent system over weakly-coupled multiple-ring-core 10-mode fibre and experimentally demonstrate single-core 7.2-Tb/s (5.64-Tb/s net rate) transmission with 800-Gb/s data rate for each of the 9 information-bearing modes using 80-GBaud probabilistic constellation-shaped 64-QAM signals.*

Introduction

As hyper-scale data centre infrastructures continue to expand, the demand for network bandwidth grows exponentially [1,2]. Self-homodyne coherent detection (SHCD) technology is proposed as a compromising coherent detection scheme for cost-sensitive high-speed optical interconnections, which eliminates the need for expensive high-stable lasers of transceivers and simplifies the digital signal processing (DSP) [3]. In the SHCD system, separate optical fibres are typically required to transmit the modulated signal and a copy of the tone as a remote local oscillator (LO) originating from the same laser to the receiver for self-homodyne coherent reception. However, additional fibres for remote LO could increase the implementation complexity. To address this, SHCD systems combined with space-division-multiplexing (SDM) based on multicore fibres (MCFs) have been proposed, in which the signals and the remote LO could be delivered in different cores of a single fibre [4,5]. As an alternative to the SDM MCFs, few-mode fibres (FMFs) can further increase the spatial channel density and achieve multiplicative capacity growth of a single fibre core. However, the development of SHCD system based on FMFs is restricted with the primary barrier of the severe modal crosstalk.

To overcome this obstacle, the weakly-coupled MDM systems with low modal crosstalk for the transmission FMF, mode multiplexer (MUX), demultiplexer (DEMUX), and their connections are required for MDM-SHCD system, in which the signals and LO can be transmitted and received independently in different spatial modes. Moreover, the complex inter-LP-mode multiple-input multiple-output DSP (MIMO-DSP) is unnecessary to undo the linear coupling [6].

In this paper, we propose an MDM-SHCD system utilizing a weakly-coupled multiple-ring-core (MRC) FMF and the matched mode MUX/DEMUX. Four rings of index perturbations in the fibre core are designed and fabricated to suppress modal crosstalk and nonlinear effect. We experimentally demonstrate a single-core 7.2-Tb/s (5.64-Tb/s net rate) MDM-SHCD transmission over 30-km weakly-coupled 10-mode fibre. One of the 10 modes transmits the self-homodyne LO and the rest are utilized for carrying 80-GBaud dual-polarization (DP) probabilistic constellation-shaped (PCS) 64-quadrature-amplitude modulation (QAM) signals. This is, so far as we know, the record capacity of a single-core weakly-coupled MDM-SHCD system. The results show that the proposed MDM-SHCD scheme paves the way for higher-capacity short-reach applications.

Multiple-ring-core 10-mode FMF and matched mode MUX/DEMUX

To suppress the modal crosstalk and nonlinear effects in the FMF for the weakly-coupled MDM-SHCD system, we have designed an MRC index

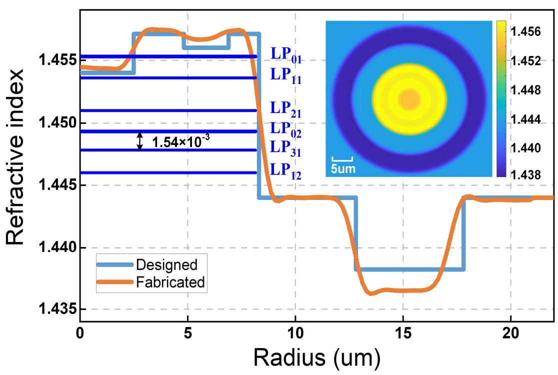

Fig. 1 Index profiles of the designed and fabricated MRC FMF, as well as the effective index of each supported LP mode. Inset: heat map of the fabricated FMF index profile.

profile of a 10-mode (6-LP-mode) FMF with large-space effective index n_{eff} and large effective areas A_{eff} of all LP modes using a multi-parameter optimization method [7]. The designed and fabricated index profiles are shown in Fig. 1. In the proposed core structure, four rings of index perturbations are utilized to separate the n_{eff} and enlarge the A_{eff} of all LP modes as much as possible. A depressed-index trench is applied in the cladding to reduce the bending sensitivity of high-order LP modes. Based on the proposed design, we have fabricated a 10-mode FMF using the plasma chemical vapor deposition (PCVD) technique. The n_{eff} and A_{eff} of 6 LP modes at 1550 nm are calculated with the fabricated fibre index profile. The min|Δn_{eff}| of the fabricated FMF is 1.54×10^{-3} lying between LP_{02} and LP_{31} modes as labelled in Fig. 1, which ensures the weak coupling among the 6 LP modes [8]. The Δn_{eff} between LP_{12} mode and cladding is adjusted to 2×10^{-3} to suppress the propagation loss originating from coupling between high-order mode and cladding mode [9]. The mode effective areas A_{eff} of all 6 LP modes are larger than 125-um^2, which is quite larger than that of conventional SMFs. Thus, the proposed FMF has less nonlinear transmission impairment and better performance over long-span transmission. Based on the improved swept-wavelength interferometry technique method [6], the distribute modal crosstalk (DMC) coefficients of the fabricated FMF for all mode pairs are measured to be lower than −28.5 dB/km.

The matched mode MUX and DEMUX consist of cascaded mode-selective couplers fabricated by side-polishing processing. The maximum back-to-back (BtB) insertion loss and modal crosstalk for the pair of mode MUX/DEMUX are 5.8 and -15 dB, respectively. The maximum modal crosstalk in 30-km FMF with a pair of MUX/DEMUX is -14.2 dB between LP_{01} and LP_{11}. Thus, LP_{01} is used for transmitting the remote LO in this work to avoid the LP_{01-11} signal crosstalk.

Experiment setup

The experimental setup for 800-Gb/s×9 MDM-SHCD transmission is shown in Fig. 2, as well as the picture of the transmission link in the inset (i). At the transmitter, the optical carrier generated by an external-cavity laser (ECL, IDPHOTONES CBMA48) with a central wavelength of 1550 nm is split into two separate paths for remote LO and signal modulation, respectively. An 80-GBaud Nyquist-shaped PCS 64-QAM (5-bits/symbol entropy) baseband signal with a roll-off factor of 0.1 is generated by an arbitrary waveform generator (AWG, Keysight M8199A) operating at 128-GSa/s, which drives a dual-polarization (DP) optical in-phase and quadrature (IQ) modulator. The output swing of the AWG is first swept and optimized to be 500 mV. The optical spectrum of the generated DP signal is presented in inset (ii) of Fig. 2. Then, the DP signal is amplified by an erbium-doped fibre amplifier (EDFA) and equally split by a 1x16 optical coupler for the 9 spatial modes, which are de-correlated with an adjacent delay difference of 150 ns. After that, the MDM signals are coupled into and out of the 30-km 10-mode fibre through the mode MUX/DEMUX.

At the receiver, the remote LO is optically amplified by an EDFA for compensating the link loss and providing LO for all spatial channels. To deal with the polarization wandering of the remote delivery LO, an optical polarization controller (PC) is used to emulate the adaptive/automatic PC [4]. For the reception of

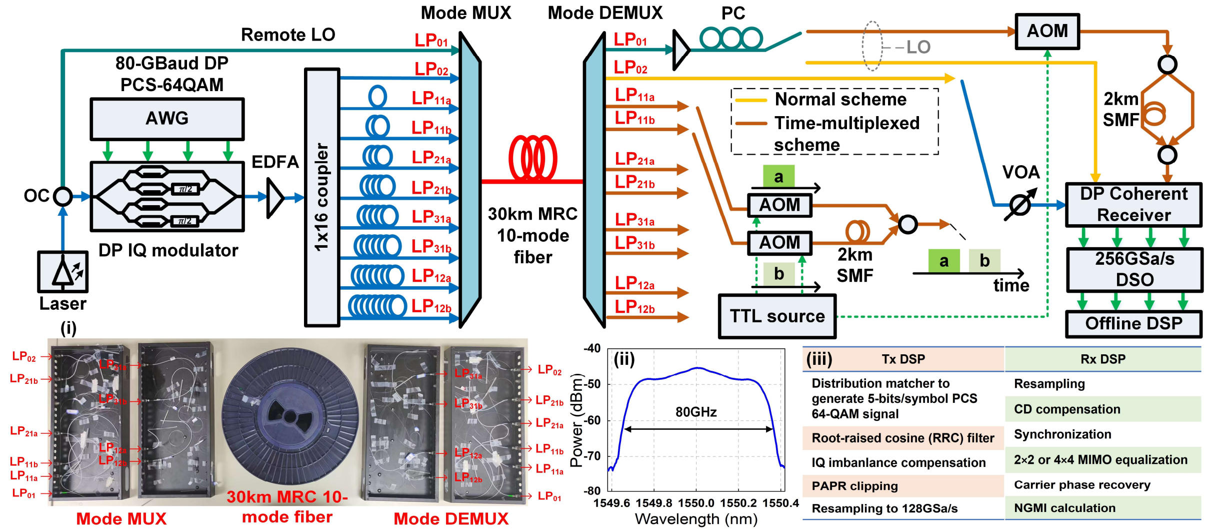

Fig. 2 Experimental setup of the 800Gb/s×9 MDM-SHCD transmission. Inset (i) the picture of the transmission link; (ii) optical spectrum of the transmitted signal; (iii) DSP algorithms employed for transmitter and receiver. PAPR: peak-to-average-power ratio; CD: chromatic dispersion; VOA: variable optical attenuator.

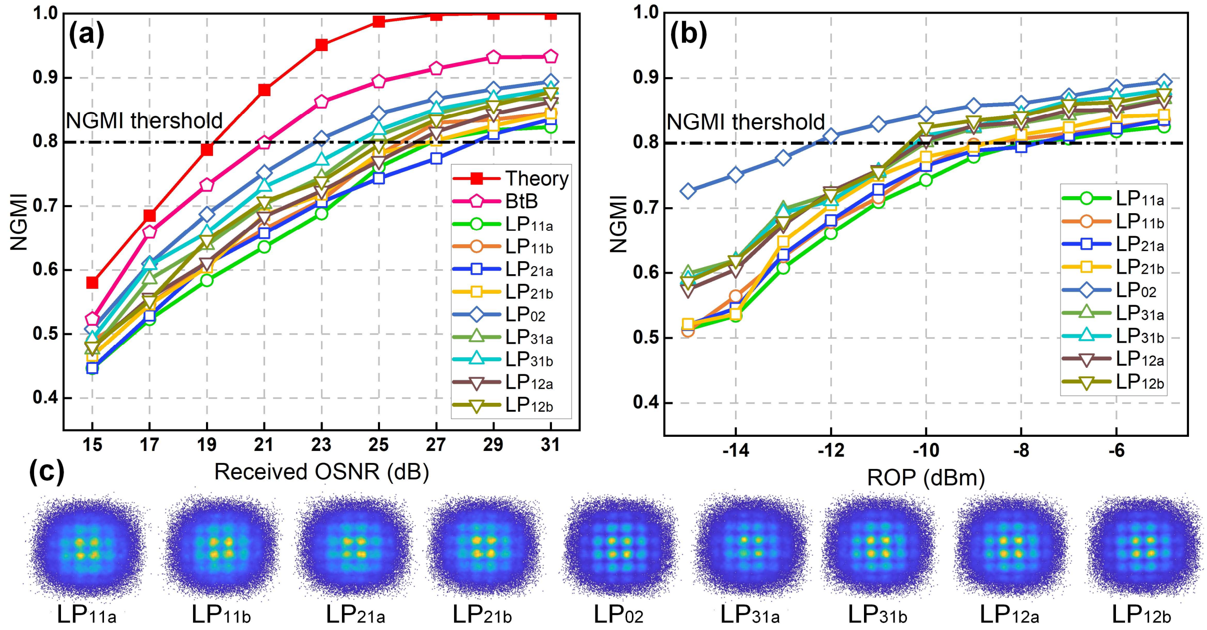

Fig. 3 Performance of the MDM-SHCD system. Measured NGMI performance of 9 mode channels versus received OSNR (a) and ROP(b). (c) Recovered PCS-64QAM constellations of the 9 mode channels at OSNR of 31dB.

degenerate LP_{mn} (m>0) modes, a time domain multiplexed (TDM) receiver scheme is adopted, 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 different time slots, while the same delay is also applied to the LO for phase matching. Three acoustic-optic modulators (AOM) driven by a transistor-transistor logic (TTL) source are used to achieve sequential control. Finally, the received electrical signals are sampled by a real-time digital storage oscilloscope (DSO, Keysight UXR0594AP) operating at 256 GSa/s for performing the offline DSP as illustrated in the inset (iii) of Fig. 2. The samples were processed by adaptive 2×2 MIMO equalizer for non-degenerate mode (LP_{0n}) or 4×4 MIMO equalizer for degenerate modes (LP_{mn}, m>0).

Results and discussion

The performance of the proposed MDM-SHD system is characterized as shown in Fig. 3. Firstly, the normalized generalized mutual information (NGMI) performance versus the received optical signal-to-noise ratio (OSNR) is swept by loading the amplified spontaneous emission (ASE) noise for both BtB and the 9 information-bearing spatial channels after 30-km MDM transmission, as shown in Fig. 3(a). We take a practical NGMI threshold of 0.8 using 27.5% SD-FEC overhead [10]. The OSNR sensitivity gap of about 2 dB at the NGMI threshold between theoretical and BtB curves mainly comes from the transceiver constraints in this experiment, which are also partially manifested by the unsuppressed optical carrier in the optical spectrum of inset (ii) of Fig. 2. The performance difference between BtB and 30-km MDM transmission of different mode channels could be mainly attributed to the modal crosstalk of the mode MUX/DEMUX. Fig. 3(b) illustrates the NGMI performance as a function of the received optical power (ROP). The performance difference between non-degenerate mode and degenerate modes could be mainly due to the additional loss originating from the OCs and AOMs in the TDM receiver. Noted that the ROP of degenerate modes is measured when the AOMs are in the all-pass state. Excluding the 27.5% FEC overhead, the achieved line rate is 7.2Tb/s and the net rate is 5.64 Tb/s for the 9 spatial modes in this experiment.

Conclusion

In this paper, we successfully demonstrate single-core 800-Gb/s×9 (5.64-Tb/s net rate) MDM-SHCD transmission using DP PCS-64QAM modulation format. The proposed 10-mode weakly-coupled MRC FMF showed good isolation among the remote LO on LP_{01} and signals on other mode channels. Our verification represents a significant step forward in realizing high spatial density, cost-effective, coherent lite solutions for next-generation data centre applications.

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