32-bit/s/Hz Spectral Efficiency WDM Transmission over 177-km Few-Mode Fiber

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Abstract: We transmit 32 WDM channels over 12 spatial and polarization modes of 177 km few-mode fiber at a record spectral efficiency of 32 bit/s/Hz. The transmitted signals are strongly coupled and recovered using 12×12 multiple-input multiple-output digital signal processing.

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1. Introduction

Increasing the spectral efficiency in optical networks is key to reducing the cost per bit. While single-mode-fiber-based transmission systems are rapidly approaching their capacity limit, space-division multiplexing over novel fiber types such as few-mode fibers and multi-core fibers is promising another significant increase in per-fiber spectral efficiency. Recently, several spectral efficiency records have been demonstrated over nominally uncoupled multicore fibers, while initial demonstrations of space-division multiplexed (SDM) transmission over few-mode fibers have focused on the feasibility of multiple-input multiple-output (MIMO) digital signal processing (DSP) over long-haul transmission distances [1–6]. In this work, we show for the first time a spectral efficiency per fiber core that significantly exceeds the theoretical limit of $\sim$ 20 bit/s/Hz predicted by the nonlinear Shannon capacity limit for a 200-km long standard single-mode fiber (SSMF) [7]. We use a few-mode fiber (FMF) supporting 12 spatial and polarization modes [6] and low-loss spatial couplers based on the photonic lantern like design [8, 9]. In our experiment, twelve 16-QAM modulated signals at a symbol rate of 20 GBaud are multiplexed onto a set of 12 orthogonal spatial and polarization modes, and further into a 32 channel wavelength-division multiplex (WDM), resulting in an aggregate capacity of 24.6 Tbit/s over a bandwidth of only 800 GHz. The signals are transmitted over three 59-km long spans of differential-group-delay-compensated fiber in a sixfold recirculating loop setup. Off-line DSP processing based on an efficient frequency-domain implementation of the adaptive linear MIMO equalizer is used to recover the signals.

2. FMF with 12 Spatial and Polarization Modes

The FMF span with a total length of 59 km was realized using multiple spools of a graded-index (GI)-FMF that support exactly 12 spatial and polarization modes that are approximated by the 4 linear modes LP_{01}, LP_{11} LP_{21}, and LP_{02}, where the LP_{11} and LP_{21} modes are twofold degenerate. The GI profile minimizes the differential group delay (DGD) between all modes across the entire C-band. Building tightly DGD-compensated spans is difficult, and it is possible to reduce the overall DGD by using multiple segments of fiber, as demonstrated in FMF supporting 3 spatial modes [4]. For FMF supporting 6 spatial modes, three DGD values must be matched and a greater diversity of compensating fiber is required. In Fig. 1 a) we show the DGD map for the compensated fiber span used in our experiment. In the DGD map the DGD values relative to the group delay of the LP_{01} mode are plotted as function of distance. The span is compensated up to 350 ps, and has a maximal excursion in DGD (time difference between the slowest and the fastest possible path) of 10.8 ns. The DGDs were measured by determining the propagation time of a 100-ps test pulse that

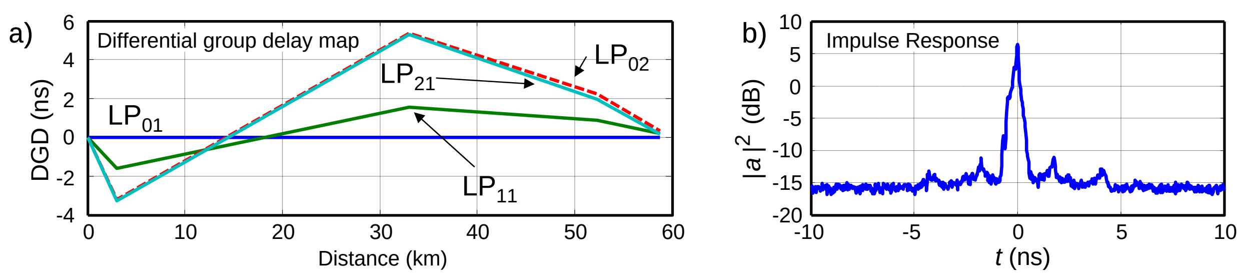

Fig. 1. a) DGD map for the 59-km compensated FMF span. b) Impulse response of the FMF span.

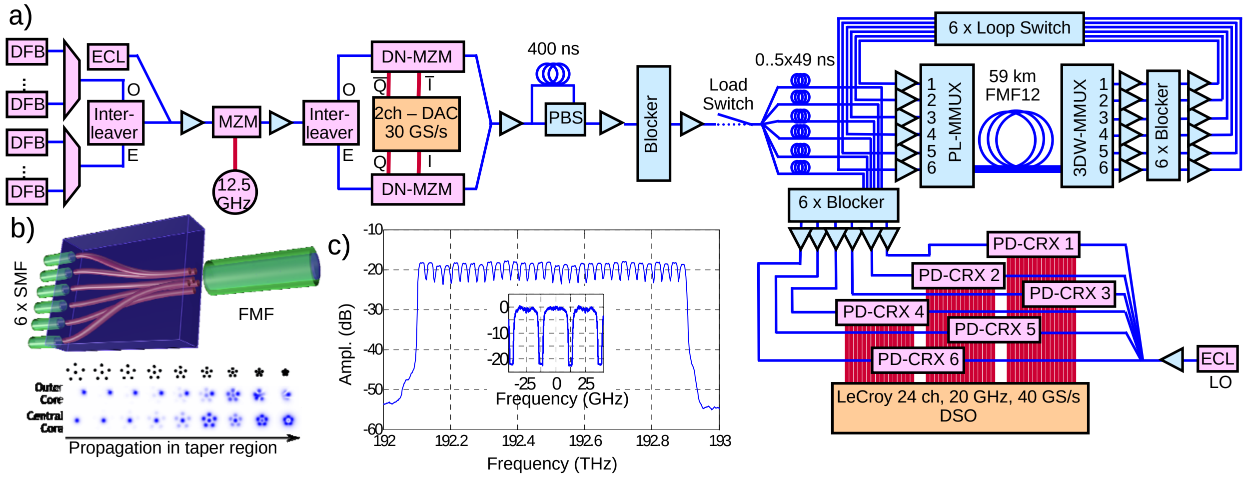

Fig. 2. a) Setup for coherent 12 × 12 MIMO transmission. EDFASs are denoted by triangles. b) Schematic design of the six-port 3DW spatial multiplexer, where 6 waveguides adiabatically merge into a multi-mode waveguide matching the FMF modes. c) Optical spectrum of the transmitted WDM signal.

was selectively coupled, one at a time, to each FMF mode by using a phase-plate-based mode coupler [1]. The FMF showed a strong coupling between the LP_{21} and LP_{02} modes in some of the fiber segments, which by design have a small difference in propagation constants. The mode coupling manifested itself as a broadening of the test pulse to around 600 ps as observed for a 10-km fiber. In contrast, sharp impulse response peaks were observed for the LP_{01} and LP_{11} modes.

The effective area of the FMF was ∼90 μm^2 for LP_{01} and LP_{11}, ∼120 μm^2 for LP_{21}, and ∼180 μm^2 for the LP_{02} mode. The loss was 0.2 dB/km for the LP_{01} mode and the chromatic dispersion was approximately 18 ps/(nm km) for all modes. The 4 fiber segments plotted in Fig. 1 a) were spliced together using a commercial fusion splicer and no significant loss originating from the splice was observed. The total span loss was 13 dB and the intensity impulse response for the composite fiber span, obtained by MIMO channel estimation followed by intensity averaging over all 12×12 individual impulse responses, is shown in Fig. 1 b). The impulse response shows an approximately 1-ns wide central peak and additional side peaks with 18 dB suppression generated the fiber splices. All peaks are contained within a 9-ns time window centered abound the main peak, suggesting that good transmission performance is expected for an equalizer windows of 10 ns.

3. 3D-Waveguide Based Spatial Multiplexers

In our experiment we use spatial multiplexers based on 3D-waveguide (3DW) design as shown in Fig. 2 b) to launch into and receive signals from the FMF. The spatial multiplexers are similar to the photonic lantern (PL) design [8, 9], and consist of multiple single mode waveguides that are brought close together to form super-modes, which approximate the modes of the FMF to be coupled into. Both couplers had nominally the same design, consisting of 6-μm cores with a refractive index contrast of $\Delta n = 0.7\%$. The cores start with a linear arrangement with a 127-μm spacing on the SSMF side and are brought together until they form the desired spot pattern consisting of a central spot and 5 off-axis spots on a radius of 7.5 μm. Because the super-modes have a larger mode-field diameter than the modes of the FMF, an imaging system with 70% magnification is used. The mode dependent loss (MDL) per coupler is 2.5 dB and insertion loss (IL) is below 3.5 dB across the entire C-band, which is only slightly larger than the theoretical values of 1.8-dB MDL and 1-dB IL. In contrast to phase-plate based couplers [1] which launch and detect signals directly from a particular LP mode, 3DW multiplexers launch signal power equally into a linear combination of modes. In coherent MIMO transmission, this distribution of the signal power across multiple modes can be undone without penalty by DSP, as long as the transformation of the coupler is unitary. In our experiment the MDL for the 59-km FMF span described in Fig. 1, including the 3DW-SMUXes was 6 dB, which typically produces good transmission performance.

4. Coherent MIMO Transmission Experiment

The transmission over the FMF span was performed according to Fig. 2 a). Thirty-two WDM channels with a 25-GHz spacing were generated by interleaving two distributed feedback laser (DFB) banks consisting of 8 lasers each spaced at 100 GHz. The resulting 16 wavelength channels spaced at 50 GHz were subsequently doubled using a $LiNbO_3$ Mach-Zender modulators (MZM) sinusoidally driven with a 12.5-GHz tone. The resulting 32 wavelengths spaced at 25 GHz were split with an interleaver and modulated using two independent double-nested $LiNbO_3$ MZM (DN-MZMs). The two DN-MZMs were driven by two 6-bit digital-to-analog converters (DACs) operating at 30 GS/s (Micram VEGA DAC II). Two De Bruijn quaternary sequences (DBQS) of length 131072 calculated from different generating polynomials, were used for the in-phase (I) and quadrature (Q) components of the 20-Gbaud 16-QAM signal. The waveforms were digitally pre-filterred with a root-raised-cosine (RRC) shape with 0.1 roll-off, and pre-emphasized for bandwidth limitations of the DACs and the DN-MZM. We used an external cavity laser (ECL) as the light source for the channel under test, and a second ECL as a local oscillator (LO) for intradyne detection. The modulated wavelength channels were passively combined and polarization multiplexed using a polarization beam splitter (PBS), introducing a delay of 400 ns (8000 symbols) between the orthogonal polarizations. The resulting polarization multiplexed signal (PDM-16QAM), was then further split into 6 paths with a relative delay of 49 ns between subsequent paths. All delays were chosen so as to produce 12 fully decorrelated signal copies across the MIMO equalizer window at the receiver. The delayed signal copies were fed to the ingress section of a 6-fold recirculating loop connected to the FMF by 3DW-SMUXs. Finally the signals are extracted from the loop and further amplified by Erbium-doped fiber amplifiers (EDFAs) followed by 6 polarization-diversity coherent receivers (PD-CRXs). The 24 electrical signals from the PD-CRXs were captured by a modular digital storage oscilloscope (DSO) (LeCroy LabMaster 9 Zi) with 24 channels, expandable up to 80 channels. The DSO was operating at 40 GS/s with a bandwidth of 20 GHz. The captured waveforms were processed off-line using the MIMO DSP algorithm described in [10] extended to support 12 channels. The algorithm implements a network of 12×12 feed-forward equalizers (FFEs) with 800 half-symbol spaced taps corresponding to an equalizer memory of 20 ns. The observed BER is in the order of

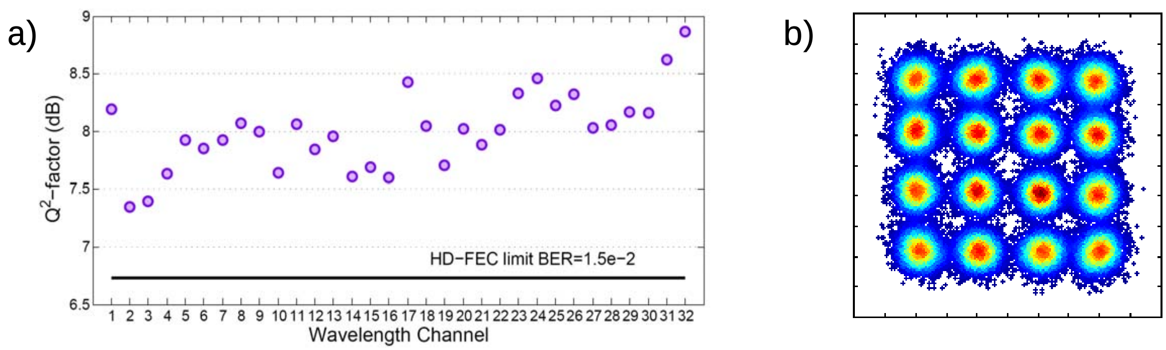

Fig. 3. a) Q-factors for 177-km transmission for all WDM channels obtained from averaging BERs over all 12 modes. b) Typical constellation after transmission.

5×10^{-5} for back-to-back measurements at high OSNR and after 177 km increases to of $< 1.0 \times 10^{-2}$, which is well below the limit tolerable for a state-of-the-art hard-decision (HD) forward-error correction (FEC) with 20% overhead. The Q-factors after transmission at an input power of -6 dBm per mode-, wavelength-, and polarization are shown in Fig. 3 a for all wavelengths. The experiment shows a spectral efficiency of 32 bit/s/Hz per core for a transmission distance of 177 km, which is the largest demonstrated in space-division multiplexed transmission.

In conclusion, we have demonstrated a record spectral efficiency of 32 bit/s/Hz per core for mode-multiplexed transmission over a few-mode fiber using 12 spatial and polarization modes using low-loss 3DW spatial couplers. A transmission length of 177 km is achieved for 32 WDM channels, resulting in an aggregate capacity of 24.6 Tbit/s over a bandwidth of 800 GHz.

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