23 Tbit/s Transmission over 17-km Conventional 50-µm Graded-Index Multimode Fiber

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Abstract: We demonstrate combined mode- and wavelength multiplexed transmission of 23 Tbit/s over 17 km conventional graded-index multimode fiber. We selectively couple and receive all spatial modes in the lowest 3 mode-groups of the multimode fiber using photonic-lanterns based mode-couplers. The transmitted signals are recovered by 12×12 MIMO digital signal processing.

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1. Introduction
Multimode fibers (MMFs) paired with VCSELs are commonly used for the lowest cost short-reach interconnects over hundreds of meters. Laser-optimized 50-µm OM4 MMF offers the benefit of favorable connector tolerances and provides standardized, effective modal bandwidth > 4.7 GHz-km at 850 nm. Stuart [1] proposed the use of spatial diversity to increase either capacity or transmission distance of multimode fibers and numerous schemes for detection, group multiplexing, and multiple-input multiple-output (MIMO) digital signal processing (DSP) have been proposed and demonstrated [2–6] nevertheless only with modest increase in transmission distance and capacity. In this work we demonstrate how to unleash the full capacity of the multimode fiber by selectively coupling into all modes of the first 3 mode groups of a MF and subsequent MIMO DSP. Selective coupling is achieved using photonic-lantern mode couplers (PLMCs) [7,8] followed by a mode filter. By transmitting a 30 Gbaud QPSK signal over 12 spatial and polarization modes a single channel line rate of 720 Gbit/s is achieved with a penalty of < 1.5 dB for a transmission distance of 17 km. Using 32 wavelength channels, spaced at 100 GHz a total line rate of 23 Tbit/s is demonstrated. This is unprecedented in MMFs opening the door for Pbit/s transmission over a single fiber core.

2. Graded-Index Multimode Fiber
The MMF span with a total length of 17 km was realized using two fiber spools with 8.3 km and 8.7 km length, respectively, and otherwise similar optical properties. Conventional graded-index, 50-µm core MMF with NA ≈ 0.2 was selected to have lower DGD at 1550 nm. Such fiber supports nine mode groups at 1550 nm, but only the first three groups comprising the LP_{01}, LP_{11}, and the LP_{21}+LP_{02}, were used in this work. The effective areas of the MMF were \sim 200 \mu m^2 for LP_{01}, \sim 265 \mu m^2 for LP_{11}, \sim 355 \mu m^2 for LP_{21}, and \sim 400 \mu m^2 for the LP_{02} mode. The loss was 0.2 dB/km for the LP_{01} mode and the chromatic dispersion was approximately 20 ps/(nm km) for all modes. The spools were spliced using a conventional fusion splicer and no particular care was applied to control the bends of the fiber which was spooled on a regular fiber spool. The total span loss was 3.5 dB and the DGD was measured by a time-of-flight arrangement using a phase-plate coupler to selectively excite the fiber modes [9]. We observed a total DGD spread of less than 4 ns for each spool, and we also confirmed that it was possible to selectively excite only particular modes (for example LP_{11} or LP_{21}) [5] and that the light would only weakly couple to other modes outside their own mode group, thus showing a coupling behavior similar as observed in few-mode fibers [9].

The intensity impulse response of the MF, obtained by MIMO channel estimation followed by intensity averaging over all 12×12 individual impulse responses, is shown in Fig. 2 c). The impulse response after 8.7 km, shows two initial distinct peaks related to the LP_{01} and the LP_{11} modes, and a double peak for the LP_{02} and LP_{21} modes. The impulse of the combined 17 km fiber is more complex, however for both fiber lengths strong suppression of the higher order modes can be observed. This is achieved by using a mode filter consisting of a 1 cm section of MMF that is tapered down from 125 µm to 40 µm using a CO2 laser based glass processor. In the taper section, the fiber will only support the desired modes, whereas the higher order modes (HOM) will leave the fiber through a refractive index matching coating placed on the cladding. All peaks are contained within a 5.3-ns time window, down from 8 ns as observed when all fiber modes are excited, suggesting that good transmission performance is expected for an equalizer window...
Fig. 1. a) Setup for 12 × 12 MIMO transmission over MMF. EDFAs are denoted by triangles. b) Schematic design and cross section of a photonic-lantern mode coupler. Six single mode fibers are place inside a low refractive index capillary and adiabatically transformed into a multimode waveguide. c) Mode profiles of the PL-MUX when input fibers are illuminated.

of 6 ns. It should be noted that this fiber is not optimized for operation at 1550 nm. Further optimization should provide lower DGD, and the DGD can additionally be compensated using, for example, mode-selective photonic lanterns [10].

3. Mode-Division multiplexing over Multimode Fibers

In our experiment mode-multiplexed transmission over MMF is achieved by: 1) Exciting and detecting all modes of the utilized mode groups, 2) Minimizing the coupling into modes of the non utilized mode groups and 3) MIMO DSP for all utilized modes. Further, assuming low crosstalk (< 4%) between the mode groups of the MMF, good performance with a full capacity gain can be expected. We use photonic-lantern mode couplers [7, 8] (PL-MUXs) to couple into the MMF (See also Fig. 1 b). The PL-MUXs are optimized to couple directly into the MMF and show an insertion loss (IL) of 2 to 3 dB and a mode dependent loss (MDL) of 4 to 5 dB. The lantern are fabricated using a CO2 laser based glass processor, by adiabatically tapering single mode fibers enclosed in a low refractive index capillary from an initial diameter of 1.6 mm to 150 µm. In order to suppress the excitation and detection of higher order mode caused by the mismatch of the PL-MUX and the MMF, mode filters are added after and before the transmit and receive PL-MUXs, respectively.

4. Mode-multiplexed MIMO Transmission Experiment

The transmission over MMF was performed using the setup shown in Fig. 1 a). Thirty-two WDM channels with a 100-GHz spacing were generated by a bank of distributed feedback lasers (DFB), combined by a wavelength multiplexer and modulated by a double-nested LiNbO3 Mach-Zender modulator (DN-MZMs). The DN-MZM was driven by two 6-bit digital-to-analog converters (DACs) operating at 30 GS/s (Micram VEGA DAC II). Two De Bruijn sequences of length 32678, were used for the in-phase (I) and quadrature (Q) components of the 30-Gbaud QPSK signal. 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) in intradyne configuration. The modulated wavelength channels were passively combined and polarization multiplexed using a polarization beam splitter (PBS), introducing a delay of 400 ns between the orthogonal polarizations. The resulting polarization multiplexed signal (PDM-QPSK), 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 connected to the MMF by PL-MUXs followed by the mode filters. After the receiving PL-MUX, the signals are amplified by Erbium-doped fiber amplifiers (EDFAs), filtered by wavelength blockers, followed with detection 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, operating at 40 GS/s with 20 GHz bandwidth. The captured waveforms are processed off line using a MIMO frequency domain equalizer (FDE) with 800 half-symbol spaced taps, corresponding to an equalizer memory of 13.3 ns. The data-aided least-mean-square (LMS) and constant modulus (CMA) algorithm were used for the FDE adaptation. We measured the bit-error rate (BER) for single channel transmission as function
of the OSNR, for single-mode fiber back-to-back (B2B), and for 10 m, 8.7 km, and 17 km MMF, respectively. Noise loading was performed at the transmitter and the results are plotted in Fig. 2. At a BER of $10^{-2}$, less than 0.8 dB penalty is observed between the signal transmitted over the MMF and B2B, and less than 2 dB penalty form the theoretical limit, confirming the excellent transmission performance. We also performed long time BER measurements at an OSNR of 14 dB. Over a 10 hours period only a small increase in BER is observed, which we believe was produced by a slight temperature dependent misalignment of the PL-MUX due to room temperature variations. We also performed BER measurements for 32 WDM channels across the C-band (from 1537.40 to 1561.42 nm), and we observed a BER $< 2 \cdot 10^{-5}$ for all channels, clearly demonstrating that longer transmission distance SDM/WDM transmission is possible over MMFs. The experiments show a single wavelength channel line rate of 720 Gbit/s, an aggregate WDM line rate of 23 Tb/s and a spectral efficiency of 7 bit/s/Hz for a transmission distance of 17 km, which to our knowledge are the largest demonstrated over MMFs to date.

5. Conclusion

We have demonstrated a record transmission rate of 23 Tbit/s over a 17 km conventional 50-µm-core multimode fiber, using photonic-lantern multiplexers followed by a mode filters in conjunction with MIMO digital signal processing. The concept is scalable to more than 3 mode groups as mode-couplers become available.

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References

4. K. Shi; et.al., IEEE Summer topical 2013