High Spectral Efficiency Mode-Multiplexed Transmission over 87-km 10-Mode Fiber

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Abstract: We demonstrate combined wavelength- and mode-multiplexed transmission with a spectral efficiency of 58 b/s/Hz over an 87-km single-span multi-mode fiber using 16-QAM modulation format. The hybrid fiber span comprises 10- and 15-mode fibers.

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1. Introduction

Large-capacity combined wavelength- and mode-multiplexed transmission over multi-mode fibers supporting 3 spatial modes [1], [2] has reached distances beyond 1000 km. Transmission using six spatial modes provided by 6-mode fiber [3], resulted in the spectral efficiency (bits/s/Hz) three times larger than the theoretical maximum capacity of single-mode fiber due to fiber nonlinear effects [4]. Successful transmission over 22.8-km 15-mode fiber [5], 4.45-km [6] 10-mode fiber and recently >100-km hybrid 10-mode and 15-mode fibers [7] has been demonstrated, which confirm that SDM is scalable to support larger number of modes. Using only quadrature phase-shift keying (QPSK), the 15mode [5] and 10-mode [7] experiments reported spectral efficiencies of 43.64 bits/s/Hz and 29 bits/s/Hz, respectively. Higher spectral efficiencies will require higher order modulation.

In this paper, we achieve a record spectral efficiency of 58 b/s/Hz per fiber core by applying 30-Gbaud 16 quadrature amplitude modulation (16-QAM) over an 87-km multi-mode fiber span composed of hybrid 10- and 15-mode fibers. The system achieves a total capacity of 67.5 Tbits/s with 30 wavelength channels.

2. 10- and 15-mode graded-index multi-mode fiber

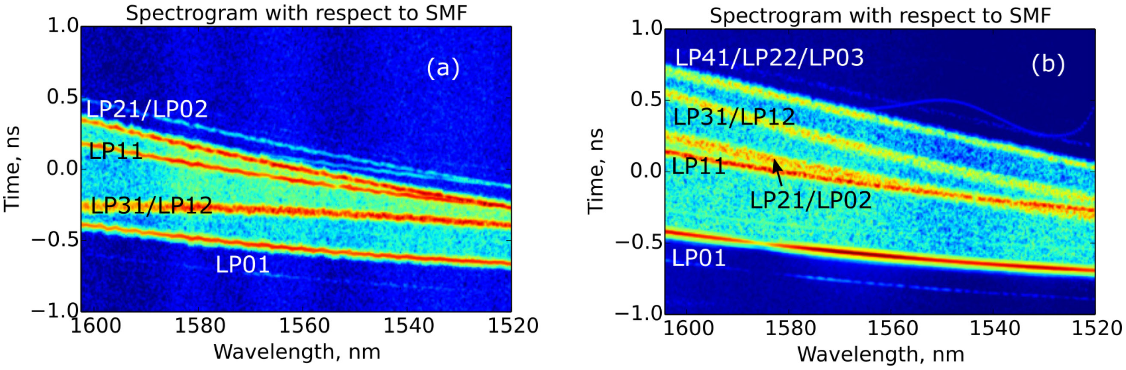

Fig. 1. Mode group spectrogram for (a) 10-mode and (b) 15-mode fiber with a length of 4.4km.

The 87-km long span has 44-km 15-mode fiber (9-LP modes) and 43-km 10-mode (6-LP modes) fiber [8]. 11 spools are spliced together using a conventional fusion splicer. In order to lower differential mode group delays (DGDs), the fibers were designed with optimized trench-assisted graded-index-core profiles. Additional efforts have also been taken to ensure low bend losses for all guided LP modes while maintaining effective cut-off for the higher-order leaky LP modes. The accuracy of the plasma chemical vapor deposition process enabled the production of such fibers with DGDs of 120 ps/km and 220 ps/km at 1550 nm for the 10-mode and 15-mode versions, respectively. The effective areas are from 117 to 270 μm^2 for the 10-mode fibers and from 95 to 215 μm^2 for the first 10-modes of the 15-mode fibers. The chromatic dispersions are between 19 and 21 ps/nm/km for all guided modes. By employing a swept laser interferometer [9], mode group spectrograms for both fibers with a length of 4.4 km are plotted in Fig. 1. The spectrogram plots the fiber intensity impulse response in the y axis versus wavelength from 1520 to 1600 nm. Different lines represent different mode groups. Four and five mode groups are present in the 10- and 15-mode fiber, respectively. It can be seen from Fig. 1(b) that the 5th mode group is responsible for the largest modal delay in the 15-mode fiber. Two short sections of 10-mode fiber were spliced to both ends of the 44-km 15-mode fiber as a mode filter to avoid coupling into the 5th mode group. Mode suppression of the 5th mode group was measured to be better than 26 dB, therefore the effect of the DGD of the 15-mode fiber could be further reduced to about 160 ps/km.

3. Photonic lantern spatial multiplexers (PL-SMUX)

Mode-group selective photonic lantern multiplexers (PL-SMUXs) are used to couple 10 modes in and out of the fiber span. The PL-SMUX is an adiabatic taper of 10 single-mode fibers into a multi-mode facet that matches the target fiber. Mode-group selectivity is obtained using dissimilar fibers and the fabrication process is reported in [10].They have insertion losses that range between 0.7 dB for the LP01 mode and 3.2 dB for the 4th mode group (LP12 and LP31). The average MDL is around 8.7 dB, which was measured by a swept laser interferometer, where a pair of photonic lanterns were connected through a 50-m piece of 10-mode fiber. Most of the IL and MDL comes from the mode mismatch at the splice point between the lantern and transmission fiber.

4. 10-mode transmission experiment

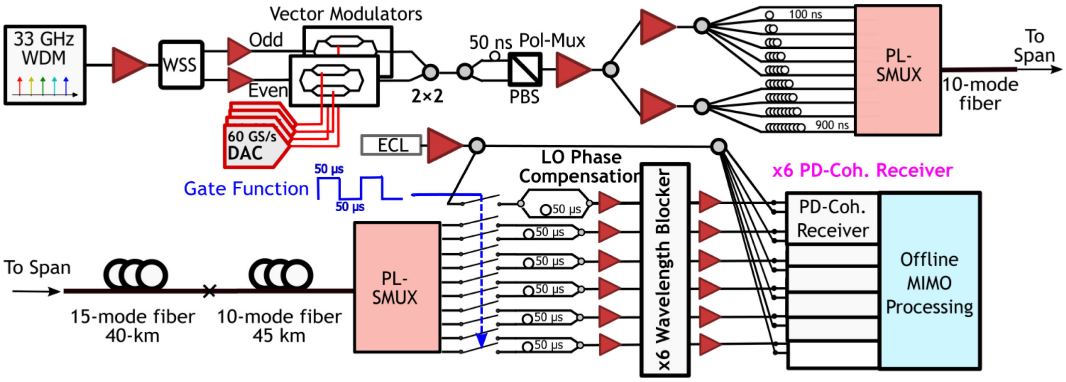

Fig. 2. Transmission setup composed of WDM transmitter, hybrid multi-mode fiber span and time-multiplexed receiver.

The transmission setup is illustrated in Fig. 2 and includes wavelength- and mode-multiplexed transmitter, hybrid multi-mode fiber span and time-multiplexed receiver. The 33.3 GHz spaced WDM comb is produced by combining multiple distributed feedback lasers (DFBs) spaced at 100 GHz using a wavelength multiplexer followed by a Mach-Zehnder modulator (MZM), which is driven with a 33.3 GHz sinusoidal signal. One external cavity laser (ECL) is used for the signal channel under test. A flexible-grid wavelength-selective switch (WSS) separated the odd and even groups which are then amplified and sent into a vector modulator, which applies 30-Gbaud 16-QAM signals. The In-phase (I) and Quadrature-phase (Q) components of the 16-QAM signals are generated by two digital-to-analog converters (DAC) operated at 60-Gsamples/s with two decorrelated sequences with a length of 2^{15}. A square-root raised cosine function with a roll-off factor of 0.01 is applied to minimize the frequency overlap between neighboring wavelength channels. 20 orthogonal signals for the two polarizations and 10 modes are emulated through delay decorrelation with a 50-ns delay between the two polarizations and 100-ns per spatial channel. The 10 decorrelated tributaries are added into the 10 inputs of a mode-selective PL-SMUX and coupled into a short 10-mode fiber, which is spliced with the 87-km hybrid multi-mode fiber span. The attenuation of the fundamental mode is 0.22 dB/km at 1550 nm, and the attenuation of the highest-order mode is 0.02-dB/km larger.

The time-multiplexed receiver measures 10 modes simultaneously using only 6 polarization-diversity coherent receivers. The 10 modes are separated by a mode-group-selective PL-SMUX and gated by 10 solid-state switches. Half of the gated signals are delayed by five 10-km SMFs (50-μs delay) and each one is combined with an undelayed signal. The switches are driven by the gating pulse with a 50% duty cycle to produce a near continuous signal on the detectors. A captured data window of 100 μs contains the data from all 10 fiber modes and polarizations. To minimize phase noise degradations, the local oscillator (LO) is also measured against itself in a separate time-multiplexed coherent receiver to capture the phase noise difference of the LO with 50-μs delay. The 6 time-multiplexed signals are sent into 6 polarization-diversity coherent receivers and the 24 output electrical signals are captured by a 40-GSamples/s digital sampling oscilloscope (DSO). Off-line digital signal processing is applied to recover the signals and the preprocessing steps include: 2 × resampling, front-end skew corrections, chromatic dispersion and frequency offset correction. Next, the 20 spatial and polarization signals are reconstructed from the 10 time-demultiplexing signal where each signal contains two modes separated by 10 km of delay (50 us). A 20 × 20 frequency-domain equalizer with 1000 symbol-spaced taps based on data-aided least-mean-square (LMS) is applied to converge the equalizer and determine the channel impulse response. For bit-error rate counting, we use the multiple-modulo algorithm (MMA) to slowly adapt the equalizer followed by carrier-phase recovery.

Transmission over 87-km hybrid multi-mode fiber is performed with both 15 and 30 wavelength channels spaced at 33 GHz. For the configuration with 15 wavelengths, all channels achieve a *Q*-factor > 7 dB, as shown in Fig. 3(a), which means conventional forward error correction (FEC) with 20% overhead can be used to recover the signals with a total capacity of 36 Tbits/s. With 30 wavelengths, the worst channels have a *Q*-factor around 6.7 dB, which requires more powerful FEC such as [11] that has FEC limit of 6.4 dB with 25% overhead. The intensity impulse responses after 43-km 10-mode fiber and 87-km hybrid fiber are plotted in Fig. 3(b) and (c). The overall MDL of the system is calculated as 10.46 dB based on all 20 × 20 input-output impulse responses.

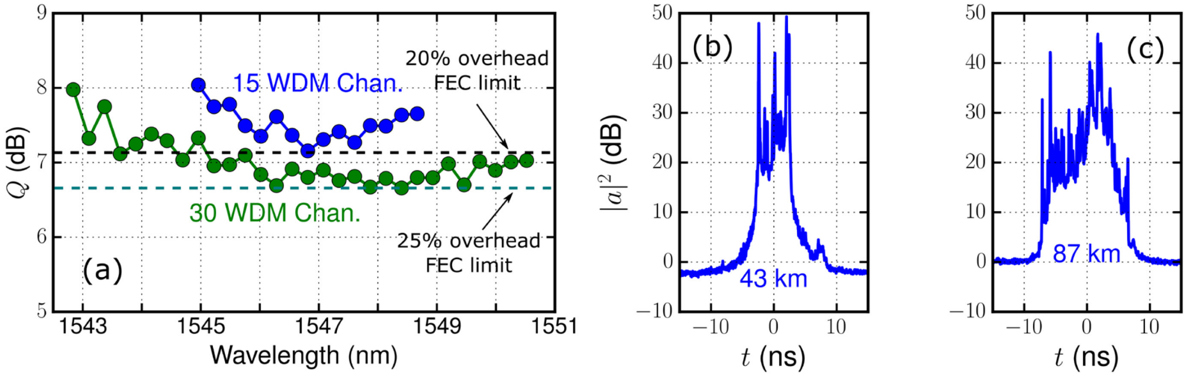

Fig. 3. (a) Q factor after 87-km transmission and intensity impulse response for (b) 43-km 10-mode fiber and (c) 44-km 15-mode fiber followed by 43-km 10-mode fiber.

4. Conclusion

We reported a successful demonstration of a record spectral efficiency of 58 b/s/Hz per fiber core by using 10 spatial modes and 16-QAM modulation format over 87-km multi-mode fiber span. By applying different FEC, total capacity of 36 Tbits/s and 67.5 Tbits/s with 15 and 30 wavelength channels can be achieved, respectively. The system reach is limited by received signal power, which can be further extended by employing high-performance multi-mode optical amplifiers.

Acknowledgements

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