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Mode-multiplexed transmission over conventional graded-index multimode fibers

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Abstract: We present experimental results for combined mode-multiplexed and wavelength multiplexed transmission over conventional graded-index multimode fibers. We use mode-selective photonic lanterns as mode couplers to precisely excite a subset of the modes of the multimode fiber and additionally to compensate for the differential group delay between the excited modes. Spatial mode filters are added to suppress undesired higher order modes. We transmit 30-Gbaud QPSK signals over 60 WDM channels, 3 spatial modes, and 2 polarizations, reaching a distance of 310 km based on a 44.3 km long span. We also report about transmission experiments over 6 spatial modes for a 17-km single-span experiment. The results indicate that multimode fibers support scalable mode-division multiplexing approaches, where modes can be added over time if desired. Also the results indicate that mode-multiplexed transmission distance over 300 km are possible in conventional multimode fibers.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications; (060.2280) Fiber design and fabrication; (040.1880) Detection; (060.4230) Multiplexing.

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1. Introduction

Optical communication networks in the era of large data centers will require link capacities with 2 to 3 orders of magnitude in excess of the capacity of single mode fibers (SMFs) [1]. Mode-division multiplexing (MDM) is currently under intense investigation as a way to overcome the capacity limits of single mode fibers. In MDM, multiple parallel signals are transmitted over a multimode fiber (MMF) carried by multiple fiber modes. The potential advantages compared to alternative approaches for space-division multiplexing (SDM) like for example the use of multi-core fibers, are significant: In MMFs the number of modes can be scaled up to 100 modes while maintaining a standard cladding diameter of 125μm. Further the strong modal overlap in MMFs can be used to build efficient multimode amplifiers where all spatial-modes are amplified at the same time similarly to the way optical amplifiers are used to amplify multiple wavelength channels in wavelength-division multiplexed (WDM) systems. Additionally, wavelength-selective switches (WSS) that support multiple modes, while maintaining a complexity comparable to traditional SMF WSS, have recently been demonstrated [2, 3]. Mode-division multiplexing, however, also presents some formidable challenges, like mode coupling and mixing in optical components and MMFs, differential group-delay (DGD) spread present between the fiber modes, and differential attenuation of higher order modes nearer to the cladding index resulting in loss of capacity.

Performing MDM transmission experiments in MMFs with 100 or more modes has proven to be very challenging, and therefore we initially started to investigate MDM in few-mode fibers (FMFs), which are MMFs with only a small number of modes. First experiments were performed in FMFs with only 3 spatial modes (LP01, LP11a, and LP11b) [4]. Over the next 3 years transmission distance was increased to over 1000 km [5, 6], number of modes increased to 6 spatial modes [7], and spectral efficiency as large as 32 bit/Hz/s [8] (which is well above the theoretical capacity limit of SMFs) demonstrated. Many results in few-mode fibers were driven by the availability of novel mode multiplexer. Laser inscribed 3D waveguide based couplers [9] and photonic lanterns [10] optimized for few-mode fiber [9], are in theory ideal mode couplers and loss below 0.5 dB have been experimentally achieved. Further, the latest generation of photonic lanterns are mode selective [11, 12], which means that they can be used to launch and receive pure fiber modes. Mode selectivity is important, because it can be used to compensated mode dependent effects like mode dependent loss (MDL) or DGD of the fiber.

The goal of this work is to investigate mode-division multiplexed transmission in conventional multimode fibers by using high performance photonic lanterns to selectively excite the mode groups of conventional MMFs. MDM in MMFs was first proposed by Faq et.al. [13] in 1982 for very short fiber lengths. In 2000 Stuart [14] demonstrated statistical mode multiplexing in combination with digital signal processing (DSP) to increase either capacity or transmission distance of MMFs and numerous schemes for detection, group multiplexing [15, 16, 17, 18], and multiple-input multiple-output (MIMO) digital signal processing (DSP) [15, 19, 16] have been proposed and demonstrated. Recent work on mode coupling into modern graded-index MMF based on spatial light modulators (SLMs) [15, 17] clearly indicates that for a MMF length of a few km, the light guided will prevalently stay within the same mode groups of the fiber, where mode groups are formed as group of degenerate modes of the MMF. In this work we make use of the relative weak coupling between the mode groups of a MMF in combination with high performance photonic lanterns to evaluate the MDM transmission performance for various MMF length for the case where only 3 or 6 spatial modes (corresponding to the

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first 2 and 3 modes groups) are used. The idea can be extended to the use of more mode groups, resulting in a scalable transmission capacity, while maintaining the same multimode fiber. Widespread commercially available fibers like the OM3 fiber, for instance, support up to 36 spatial modes at a wavelength of 1550 nm, offering a potential capacity well above 1 Pbit/s. However it should be noted that the effective index of the highest order mode group in conventional 50μm MMF designs can be very close to the cladding index; this may serve as an effective means of leaking power out of the ladder of modes, limiting the transmission capacity.

We first present experimental results performed in a 44.13 km long span of OM3 multimode fiber [20], where we transmitted a 30-Gbaud QPSK signal over 3 spatial modes, 2 polarization channels and 60 WDM channels, for a distance of 310 km by making use of a recirculating loop. A capacity of 18 Tbit/s and a spectral efficiency of 9 bit/s/Hz, which results in a spectral-efficiency-distance product of 2790 bit/s/Hz km, which is almost twice the previous record [21] set by using only the fundamental mode of an OM3 MMF. The results were obtained by using high-performance mode-selective photonic lanterns (MS-PHL) that allowed us to precisely excite and detect only the desired modes and also perform external compensation of the differential group delay of the MMF. Additionally, we used all-fiber based mode filters to attenuate undesired higher order fiber modes.

In a second experiment, we demonstrated transmission of 23 Tbit/s using 6 spatial modes, however using a relative short conventional MMF fiber with a length of 17 km [22]. By transmitting a 30-Gbaud QPSK signal over 6 spatial and 2 polarization modes a single channel line rate of 720 Gbit/s is achieved with a penalty of < 1.5 dB. Using 32 WDM channels with a 100-GHz spacing, a total line rate of 23 Tbit/s is demonstrated. This is unprecedented in MMFs and clearly demonstrates the potential of multiplexing independent data streams in standard multimoded fiber. However, it should be noted that modern multimode fibers have also been specially designed to reduce the loss of the highest order mode group intended for transmission, and thus reduce the differential mode attenuation, and may present distinct advantages for transmission capacity and distance [23]. Those advantages may be strongly manifested in practical deployments with frequent splices over long distances. Such designs specifically configure the modes not intended to transmit data to have effective indices near the cladding index so as to be leaky, and they configure the index spacing between the desired mode having the lowest effective index and the leaky mode with the highest effective index to be sufficiently large so as to limit coupling between them.

2. Graded-index multimode fibers for mode-division multiplexing

Conventional MMFs are widespread for short reach optical interconnect applications because of their relaxed connector tolerances and the efficient and low cost coupling to low cost laser sources like Vertical-cavity surface-emitting lasers (VCSELs). Coupling tolerances in the lateral position accuracy of the MMF are achieved by using core diameters of 50 μm which are 6 times larger than in a standard single mode fiber (SSMF), whereas tolerance to angular misalignment of the MMF core is provided by the presence of multiple modes. As beneficial as the presence of multiple mode is for fiber coupling, it can causes significant impairments for high data rate transmission. A transmitted signal that is coupled into multiple modes will suffer from modal dispersion as each mode travels with a different group velocity and multiple time delayed copies of the signal will appear at the end of the MMF. In order to mitigate the effect of modal dispersion, modern MMFs use cores with a graded index refractive-index profile which minimize the group velocity spread and MMFs optimized for 850-nm wavelength can typically provide modal bandwidth in excess of 5 GHz km. In addition, in order to reduce bending losses in MMF, a low refractive index ring profile (depressed cladding) is added around the core, which results in a clean cut-off for the highest order modes, an stylized index profile is shown

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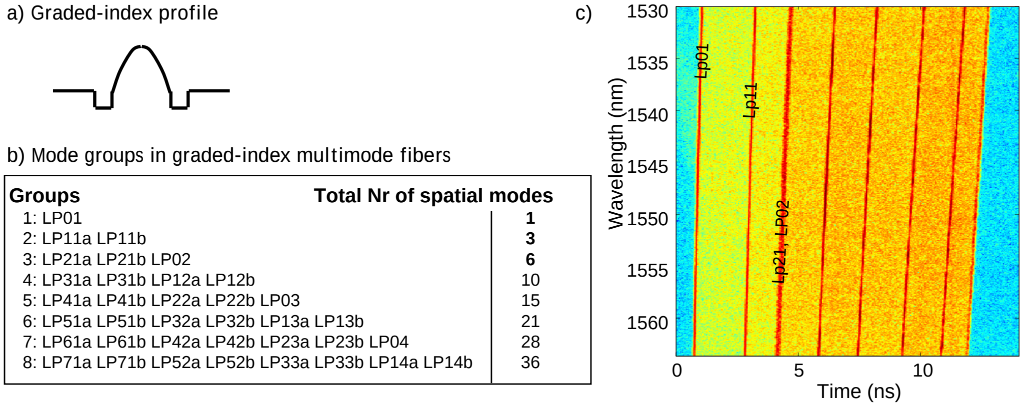
in Fig. 1(a). The resulting fibers offer several modal properties that are favorable for mode-division multiplexing [15, 17]. In this work we investigated bend insensitive commercial OM3 MMF. The graded-index MMF had a 50-µm core diameter and was optimized for maximum modal bandwidth at 850 nm. When used at a wavelength of 1550 nm the fiber supports 9 mode groups. Each mode group is formed by a set of degenerate modes which are reported in Fig. 1(b) by using the linear polarized mode (LP) notation. The total number of spatial modes is obtained by counting all modes including the degenerate modes (for example LP11 is counted twice as it is two fold degenerate). For 8 mode groups the resulting total number of spatial modes is 36. The fiber loss at 1550 nm of the OM3 MMF was measured to be 0.34 dB/km for the LP01 and LP11 modes and the chromatic dispersion was approximately 20-24 ps/(nm km). The fiber spool with a length of 8.861 km was characterized using swept laser interferometry [24, 25] and the results are reported in Fig. 1(c) as spectrogram, where the fiber intensity impulse response is reported as function of the wavelength in a range from 1530 to 1560 nm. The mode groups appear as lines and we identified the corresponding lines for the first 3 groups by using a phase-plate based mode multiplexer. Further we identified the sequence of the higher order modes using a simple off-axis launch from a single-mode fiber. Figure 1(c) shows that the mode groups are clearly separated confirming that crosstalk between mode groups is relatively small. This property is essential for our transmission experiments as we only excite a subset of mode groups. Note that the measurement shown in Fig. 1(c), does not provide precise quantitative measurements of the crosstalk, as not all fiber modes are excited. The single shot measurement was performed using an off-axis launch such that mode groups contained approximately the same peak power.



Groups	Total Nr of spatial modes
1: LP01	**1**
2: LP11a LP11b	**3**
3: LP21a LP21b LP02	**6**
4: LP31a LP31b LP12a LP12b	10
5: LP41a LP41b LP22a LP22b LP03	15
6: LP51a LP51b LP32a LP32b LP13a LP13b	21
7: LP61a LP61b LP42a LP42b LP23a LP23b LP04	28
8: LP71a LP71b LP52a LP52b LP33a LP33b LP14a LP14b	36

Fig. 1. a) Exemplary index profile of a graded index multimode fiber. b) Relation between LP modes, spatial modes and mode groups in multimode fibers. c) Mode group Spectrogram of a 8.861 km multimode fiber. The horizontal axis represents the time response and the vertical axis represents the measurement wavelength.

In our experiments mode-multiplexed transmission over MMF is achieved by:

- Exciting and detecting all the modes that are part of the utilized mode groups
- Minimizing the coupling into modes of the non utilized mode groups
- Processing with multiple-input multiple-output (MIMO) digital signal processing (DSP) over all utilized modes
- Optionally reducing the modal crosstalk build-up during propagation by adding spatial filters

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Assuming low crosstalk ($< 4\%$) between the mode groups of the MMF, good performance with a full capacity gain can then be expected. The effect of crosstalk into modes of the not utilized groups, can be further reduced by introducing mode filters along the MMF span.

3. Mode-multiplexed MIMO Transmission with 3 spatial modes

A MMF span with a total length of 44.315 km was realized using 5 spools of approximately 8.9-km long OM3 fiber which were spliced together using a CO_2-laser-based glass processor with high resolution imaging optics to visually confirm the quality of the fiber cleave before splicing and also inspect the quality of the obtained splice. Cleave angle in particular, is critical in order to obtain a splice with low crosstalk between the modes.

The DGD values were measured using swept laser interferometry and are reported in Tab. 1 for the first three mode groups. The measured values are similar for all 5 spools, showing a DGD relative to the fundamental mode (LP01) of around 1.4 ns for LP11 and 2.6 ns for the LP21/LP02 modes. The total DGD between the LP01 and LP11 modes for the 44.3 km span was 7.7 ns, which is short enough to be captured by our digital signal processing (DSP) multiple-input multiple-output (MIMO) equalizer windows for a single span experiment, but cascaded spans will require DGD compensation.

Table 1. Fiber properties of the 5 multimode fiber spools composing the transmission span. L: Fiber length, DGD_{LPXX}: Delay between LP01 and LPXX mode, respectively.

Spool Nr	L (km)	DGD_{LP11} (ns)	DGD_{LP21} (ns)	DGD_{LP31} (ns)
1	8.861	1.5	2.8	4.3
2	8.861	1.6	2.9	4.6
3	8.851	1.5	2.7	4
4	8.871	1.5	2.6	3.9
5	8.871	1.6	2.8	4.2
Total	44.315	7.7	13.8	21

DGD compensation was achieved using a mode-selective mode multiplexer, followed by single-mode fibers of different length, chosen to undo the modal delay accrued in the fibers. The principle of operation in shown in Fig. 2. High performance mode-selective mode multiplexers with more than 20-dB mode selectivity and less than 0.5-dB insertion loss, were fabricated based on the mode-selective photonic lantern design as described in [11]. We used a MS-PHL on both ends of the span, and to additionally attenuate undesired higher order modes present in the MMF, we used a mode filter realized by winding 10 loops of MMF on a 6 mm diameter post. The filters were placed before each splice of the MMF span. The correct alignment of the MS-PHL in respect to the MMF was monitored accurately using a swept laser interferometer, and the effectiveness of the modal filter was confirmed by monitoring the impulse response of the fiber with and without modal filter. The analysis of the impulse response showed that the spatial filters had no impact on the transmission of the LP01 and the LP11 modes, but we observed a clear attenuation of the higher order modes. The span was then inserted into a 3-fold recirculating loop setup (see Fig. 3(a)) in order to measure the effect of cascaded MMF spans. The setup uses twenty distributed feedback lasers (DFBs) covering a wavelength range from 1538.98 to 1554.13 nm and spaced at 100 GHz, which are combined to form a wavelength comb by a wavelength multiplexer. During the measurement, the DFB laser corresponding to

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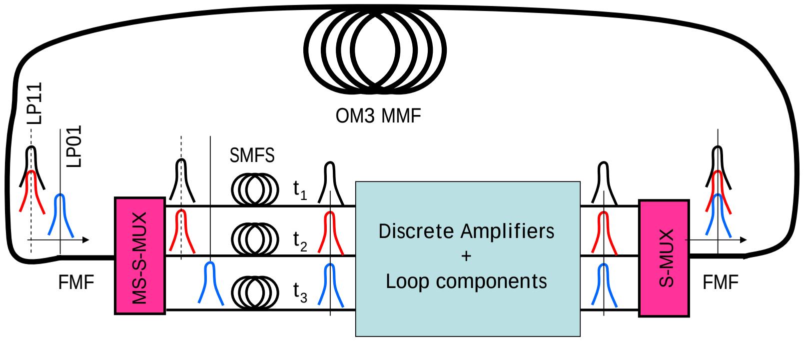

Fig. 2. Differential group delay compensation in recirculating loop experiment. The time delay introduce by the by the difference in group delay between the modes is compensated using single mode fibers od different length after the MS-PHL.

the channel under test was turned off and replaced by an external cavity laser (ECL) with a 100-KHz linewidth. The ECL was added to the comb using a 3-dB coupler. The number of lines in the frequency comb is subsequently tripled using a $LiNbO_3$ Mach-Zender modulators (MZM) sinusoidally driven with a 33.33-GHz tone. The resulting 60 wavelengths spaced at 33.33 GHz were split by a flexible-grid wavelength-selective switch (WSS) and modulated by two double-nested $LiNbO_3$ Mach-Zender modulator (DN-MZMs). The DN-MZMs were driven by four 8-bit digital-to-analog converters (DACs) operating at 60 GSamples/s. Two De Bruijn sequences of length 65536, were used for the in-phase (I) and quadrature (Q) components of the spectrally shaped 30-Gbaud QPSK signal, where a root-raised-cosine (RRC) filter with a roll-off factor of 0.1 was applied to avoid crosstalk from neighbor wavelength channels. The modulated wavelength channels were passively combined using a 3-dB coupler and polarization multiplexed using a polarization beam splitter (PBS), introducing a delay of 382 ns between the orthogonal polarizations. The resulting polarization multiplexed signal (PDM-QPSK), was then further split into 3 paths with a relative delay of 49 ns and 99 ns, respectively. The delayed signal copies were then injected into a 3-fold recirculating loop, with each individual loop consisting of a two-stage Erbium doped fiber amplifier (EDFA), where a wavelength blocker, a loop switch and a 3-dB coupler were placed between the stages of the EDFA. Each loop was precisely adjusted in length to match the loop round-trip time to within 100 ps. The signals

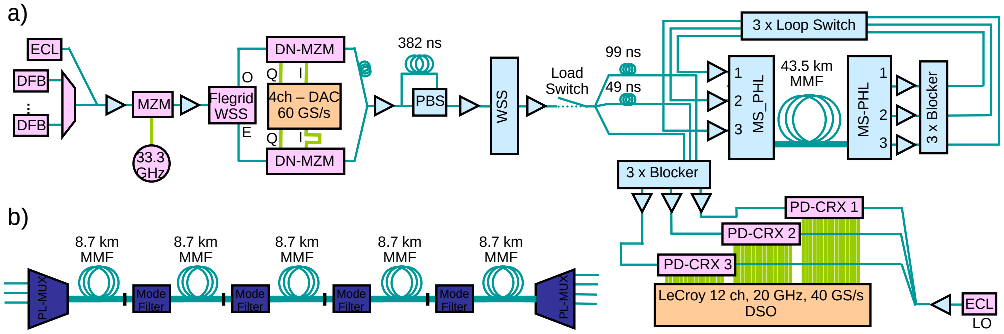

Fig. 3. a) Schematically setup for the mode-multiplexed transmission experiment over 44.3-km multimode fiber. Triangles denote EDFAs. b) Configuration of the multimode fiber span.

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extracted from the loop are then fed to a second set of two-stage EDFAs where a second set of blockers are placed between the stages to select the channel under test. The amplified signals are then sent to 3 polarization-diversity coherent receivers (PD-CRXs), where a second ECL was used as a local oscillator (LO) in intradyne configuration. The 12 resulting electrical signals from the PD-CRXs were captured by a modular digital storage oscilloscope (DSO) with 12 channels, operating at a sampling rate of 40 GS/s and a bandwidth of 20 GHz. The captured waveforms were processed off-line using a 6×6 MIMO frequency domain equalizer (FDE) with 1000-symbol spaced taps, corresponding to an equalizer memory of 33.3 ns. Data-aided least-mean-square (LMS) algorithm was used on the first million samples in order to force the convergence of the equalizer coefficients, followed by the constant modulus (CMA) algorithm to track changes in the transmission and error counting [26].

The impulse responses for the 6×6 MIMO channels were obtained by a channel estimation and are reported in Fig. 4, for different combination of launched and received LP modes: The top-left plot shows the impulse response when the LP01 mode is launched and received. The bottom-right plot shows the impulse response for launching and receiving LP11 modes. The bottom-left plot shows the impulse response when LP01 is launched and the LP11 mode received, and finally the top-right plot reports the impulse response when a LP11 mode is launched and the LP01 mode received. Note that we average over all combination of the degenerate LP11 modes as well as all polarizations as the corresponding impulse responses are very similar. Further each plot reports the corresponding impulse response for various distances starting with a single span result (44.3 km), followed by cascaded spans at distances of 89, 133, and 310 km respectively. The measurements show that DGD is correctly compensated (main peaks in top-left and bottom-right plots are overlapping in time), and that most of the signal resides in the central peaks after a single span. The impulse response of the LP01 mode behaves similarly as observed in few-mode fibers [5], most of the energy is confined in the 0 to 7.7 ns windows as expected if the effect of modes higher than LP11 are negligible, which indicates that the MS-PHL can excite a very pure LP01 mode with a good suppression of higher order modes (HOM) such as the LP0n modes. This was also confirmed by the characterizing the ML-

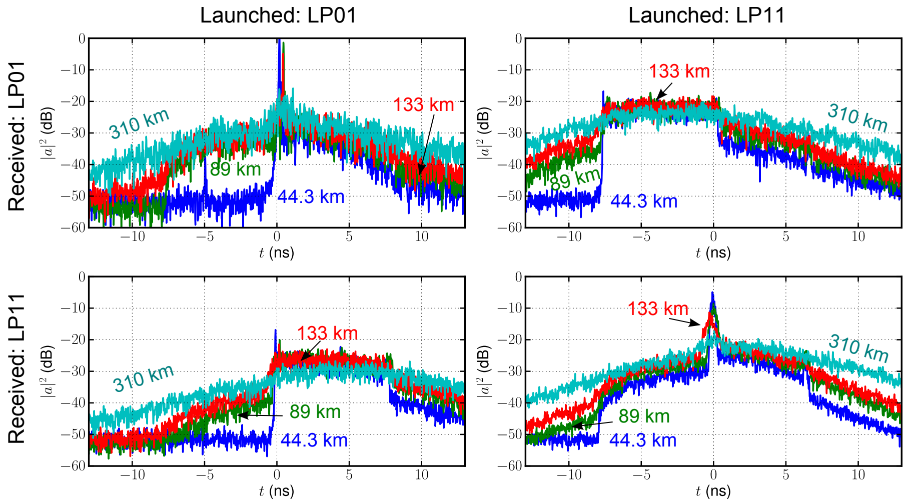

Fig. 4. Intensity impulse responses of a cascaded 44.3 km multimode fiber span after DGD compensation by mode-selective photonic lantern. The Intensity averaged impulse responses are reported for various combination of launched and received LP modes for distances of 44.3, 89, 133, and 310 km, respectively.

PHL with a 50 m short MMF connected and measuring the reflection from the end facet of the MMF using swept-laser interferometry, where a HOM suppression of > 40 dB was observed. When an LP11 mode is launched and received, we observe the FMF-like behavior for negative values of the time axis, but we can also see a considerable contribution for times from 0 to 6.5 ns that indicates the presence of additional HOM. The drop at 6.5 ns is a strong indication of the dominance of the LP21 mode, but additional HOM are observable even for times > 6.5 ns. The presence of the LP21 mode was also confirmed by performing swept laser interferometry on a 50-m MMF, where a suppression between LP11 and LP21 mode of > 20 dB and a suppression between LP01 and additional HOM of > 40 dB was measured. Therefore the HOM contribution for times > 6.5 ns has to be attributed to crosstalk in the fiber and the splices between the fiber spools. The impact of crosstalk is significant for the cascaded spans. After 89 km the impulse responses only widen slowly showing the clear advantage of DGD compensation. The contribution of crosstalk however grows significantly, after 133 km the impulse responses start to morph into bell-shaped curve, and all impulse responses are bell-shaped after 310 km.

The transmission performance was evaluated by calculating the average bit-error rate (BER) across all spatial and polarizations modes and subsequently transforming them into Q factors. The average Q factors calculated this way are representative for the system performance as the strongly mixed spatial and polarization channels are indivisible and form a spatial super-channel, and the transmitted data can be coded across all spatial and polarization channels. The Q factors for all 60 WDM channels are reported in Fig. 5 as function of distance. For completeness, we also included for each wavelength channel the corresponding Q factor for the worst and best spatial and polarization channel, which are reported in Fig. 5 as vertical bars around the average Q factors. An average $Q > 7$ dB is observed for all WDM channels for a distance up to 310 km, and all the transmitted data can be successfully recovered if forward error correction (FEC) with 20% overhead is applied to the aggregated spatial super-channel. The experiments show a single wavelength channel capacity of 300 Gbit/s, an aggregate WDM capacity of 18 Tb/s and a spectral efficiency of 9 bit/s/Hz for a transmission distance of 310 km, which results in a spectral-efficiency-distance product of 2790 bit/s/Hz km which is the largest demonstrated over MMFs to date.

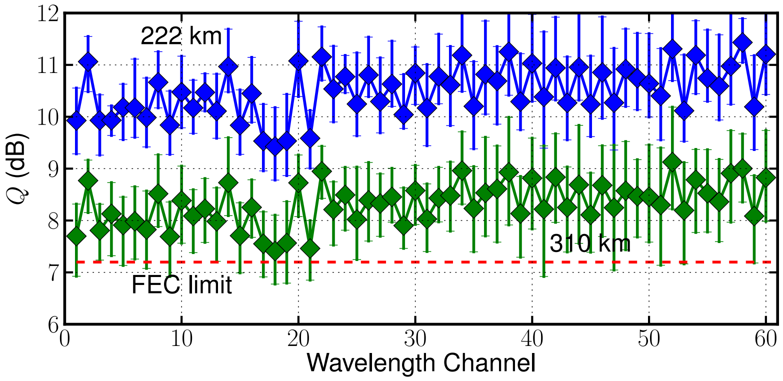

Fig. 5. Q-factor as function of the distance for all WDM channels.

4. Six spatial mode transmission over graded-index multimode fiber

We also performed mode-multiplexed transmission over conventional graded index MMF using 6 spatial modes. We used a MMF span with a total length of 17 km that was realized using two

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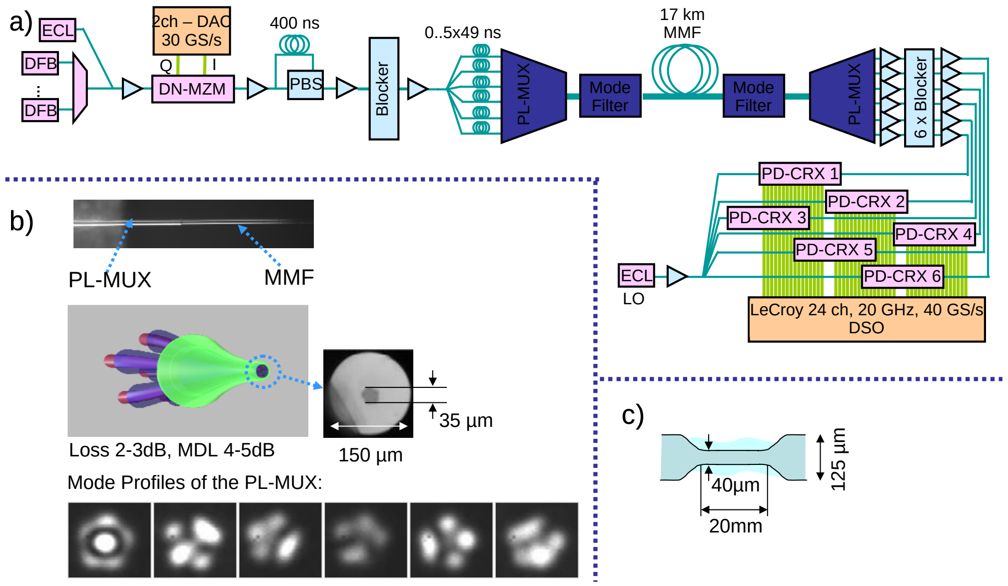

Fig. 6. a) Setup for 12 × 12 MIMO transmission over MMF. EDFAs are denoted by triangles. b) Schematic design and cross section of a photonic-lantern mode coupler. Mode profiles of the PL-MUX when input fibers are illuminated are shown in the bottom left. c) Schematic design and dimensions of the spatial filters.

fiber spools with 8.3 km and 8.7 km length. The fiber was a conventional graded-index, 50-µm core MMF with NA ≈ 0.2 that was selected to have lower DGD at 1550 nm. The fiber supported nine mode groups at 1550 nm, and the first three groups comprising the LP_{01}, LP_{11}, and the LP_{21}+LP_{02}, were used for transmission. The effective areas of the MMF were ~200 µm^2 for LP_{01}, ~265 µm^2 LP_{11}, ~355 µm^2 for LP_{21}, and ~400 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 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 [27]. We observed a total DGD spread of less than 4 ns for each spool across the selected groups and the fiber showed similar mode coupling properties as the fiber described in Sec. 2. We used 6-spatial-mode photonic lanterns that were not mode selective, followed by optical mode filters introduced into the MMF close to the photonic lanterns. The spatial mode filter consisted of a 1 cm section of MMF that is tapered down from 125 µm to 40 µm using a CO_2 laser based glass processor (see also Fig. 6(c)). In the taper section, the fiber only supports the desired number of modes, whereas the higher order modes (HOMs) will leave the fiber through a refractive index matching coating placed on the bare cladding. The average intensity impulse response of the MMF, obtained by MIMO channel estimation followed by intensity averaging over all 12×12 individual impulse responses, is shown in Fig. 7(c). The impulse response after 10 m MMF shows a strong narrow peak as expected, and some small peaks (suppressed by $>$ 40 dB) which are most probably caused by cladding modes. 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, whereas the impulse response of the combined 17 km fiber is more complex, however for both fiber lengths, strong suppression of the higher order modes can be observed. 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 length of 400-symbols spaced taps. The results also indicate that transmission over spans up to 35 km should be possible when equalizers with more taps are used. It should be noted that this fiber was not optimized for operation at 1550 nm. Further optimization of the fiber design should provide even lower DGD spread allowing for longer spans. Longer transmission distances should also be possible by using mode-selective 6-mode PL-MUXs and a recirculating loop similarly as presented in Sec. 3 for 3 spatial modes.

The transmission experiment supporting 6 spatial modes is shown in Fig. 6(a). The experiment is similar to the setup described in Sec. 3. The main difference is that the transmitted WDM signal is different: it consists of thirty-two WDM channels with a 100-GHz spacing were, carrying a 30-Gbaud QPSK signal generated by a single DN-MZM driven by two 6-bit digital-to-analog converters (DACs) operating at 30 GS/s (Micram VEGA DAC II). Also the setup was modified to support 6 spatial modes, and the recirculating loop was removed. The same off-line MIMO DSP was applied to evaluate the transmission performance, except that the number of symbol spaced equalizer taps was reduced to 400 corresponding to an equalizer memory length of 13.3 ns. We measured the bit-error rate (BER) averaged over all spatial and polarization channels for single wavelength-channel transmission as a function of the OSNR, for single-mode fibers in back-to-back (B2B), and for 10 m, 8.7 km, and 17 km of MMF, respectively. Noise loading was performed at the transmitter, the wavelength was 1548.50 nm, and the results are plotted in Fig. 7(b). 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.The results are reported in Fig. 7(d). Over a period of 10 hours 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 fluctuations. We also performed BER measurements for 32 WDM channels across the C-band (from 1537.40 to 1561.42 nm), reported in Fig. 7(a), where the vertical bars indicate the BER range for the best and worst spatial and polarization channels. For all 32 channels, the best spatial and polarization channels had no errors over the million samples used for error counting. Wavelength channel 21 was error free for all spatial and polarization channels. Further we

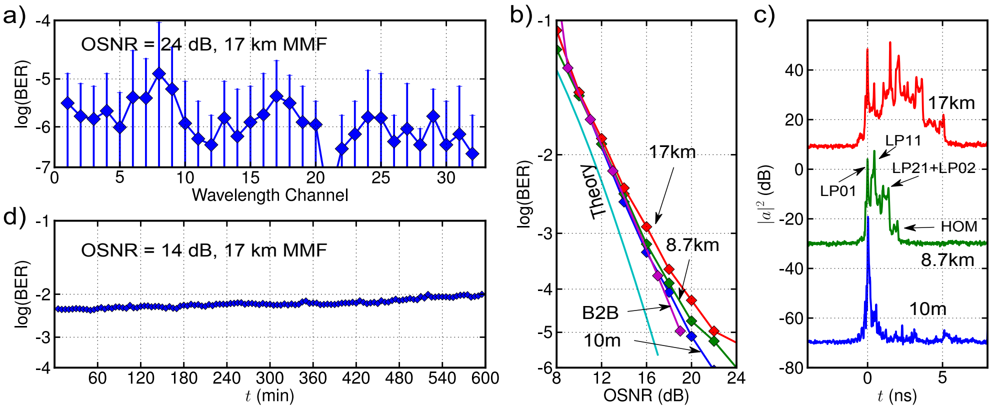

Fig. 7. a) BERs for 32 WDM channels ranging from 1537.40 to 1561.42 nm. b) BER as function of OSNR plotted for back-to-back, and 10 m, 8.7 km, and 17 km of MMF. c) Intensity impulse response of the MMF for as function of MMF length d) Long-term BER measurement for 17 km MMF.

observed a BER averaged over all spatial and polarization channels $< 2 \cdot 10^{-5}$ 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 this is the largest single channel line rate reported in MMFs to date and spectral efficiency in excess of 20 bit/s/Hz should be possible to be reached by reducing the WDM channel spacing from 100 GHz to 33.3 GHz. The results confirm that mode-division multiplexing over MMFs can be scaled to 6 spatial modes. We believe that the approach is also scalable to more modes, and in particular the use of spatial filters may become unnecessary as the number of transmitted modes approaches the total number of guided fiber modes. In that regime, however, the transmission performance could potentially be limited by the mode-dependent loss of high order modes caused by coupling into leaky modes.

5. Conclusion

We have demonstrated mode-multiplexed transmission over conventional 50-µm core diameter graded index multimode fibers. We have demonstrated transmission over 3 and 6 spatial modes, but the approach is scalable up to 36 modes in OM3 multimode fibers. For 3 spatial modes we have a achieved a transmission distance of 310 km with a capacity of 18 Tbit/s and a spectral efficiency of 9 bit/s/Hz, using mode-selective photonic-lantern mode multiplexers for differential group-delay compensation in combination with spatial mode filters and MIMO digital signal processing. We also demonstrated a transmission distance of 17 km for mode-multiplexed transmission over 6 spatial modes with a single 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. The demonstrated approach is scalable and works with existing and commercially available multimode fibers, subject to the caveats previously noted.

Acknowledgments

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