Coherent 1200-km 6 x 6 MIMO Mode-Multiplexed Transmission over 3-core Microstructured Fiber

R. Ryf*, A. Sierra*, R.-J. Essiambre*, A. H. Gnauck*, S. Randel*, M. Esmaeelpour*, S. Mumtaz*, P. J. Winzer*, R. Delbue†, P. Pupalaikis†, A. Sureka†, T. Hayashi‡, T. Taru‡, and T. Sasaki‡

**Bell Laboratories, Alcatel-Lucent, 791 Holmdel-Keyport Rd, Holmdel, NJ, 07733, USA.*
†LeCroy Corporation, 700 Chestnut Ridge Road, Chestnut Ridge, NY 10977, USA
‡Optical Communications R&D Laboratories, Sumitomo Electric Industries, 1,Taya-cho, Sakae-ku, Yokohama, Kanagawa, Japan.

Roland.Ryf@alcatel-lucent.com

Abstract: We experimentally demonstrate transmission of 6 mode-multiplexed 20-Gbd-QPSK signals over 1200 km of three-core microstructured fiber (3C-MSF). An aggregate single-wavelength capacity of 240 Gbit/s is recovered by off-line 6×6 coherent multiple-input multiple-output (MIMO) digital signal processing.

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1. Introduction

Improving the characteristics of single-mode fibers through a reduction in loss coefficient or increase in effective area, has been shown to only modestly increase the fiber ultimate capacity [1]. In order to achieve a leap in capacity, mode multiplexing in fibers has recently been proposed [2] followed by several experimental demonstrations [3–6] in few-mode single-core fibers. In this paper, we make use of a new type of transmission fiber, the 3C-MSF, fabricated from three large effective area cores closely packed together to create a low-core-number raised-index all-solid-glass microstructured fiber [8]. As for the few-mode single-core step-index fiber (SI-FMF), the 3C-MSF supports multiple modes, also called "super-modes [7] for this type of fiber. The fabricated fiber supports 6 spatial- and polarization modes available for mode multiplexing. The 3C-MSF approach has several advantages compared to SI-FMF: individual mode excitation is simpler with typically lower insertion loss, the modes show lower differential group delay (DGD), and most importantly, the 3C-MSF can easily be microstructured to achieve a set of desired fiber characteristics by changing the number, location and characteristics of the cores. Note that, in this paper, the transmitted channels are launched into individual cores by taking advantage of the fact that a unitary transformation between 3C-MSF modes and core modes does not impact capacity for identical channels [9].

In this work we make use of the low-DGD super-modes of a 3C-MSF, to demonstrate mode-multiplexed 6×6 coherent MIMO transmission at a record distance of 1200 km. This is achieved by using a path-length-matched parallel-loop experiment, where the 3 cores of a 60-km 3C-MSF span are traversed up to 20 times. The 6 transmitted 20-GBd-QPSK channels are recovered at the receivers using off-line 6×6 MIMO processing. This is, to our knowledge, the first 6×6 MIMO loop experiment, and the distance demonstrated is 12 times longer than the record single span distance of 96 km over FMF presented in [11].

2. The three-core microstructured fiber

The 3-core fiber has homogeneous cores with a diameter of 12.4 μm and a refractive index difference $\Delta = 0.27\%$. The distance between the cores is 29.4 μm, and the resulting distance between the cores and the center of the fiber is 17 μm. The fiber has a standard cladding diameter of 125 μm, and the effective area of each core was measured to be $(129\pm2)\mu\text{m}^2$. In comparison to [10] the distance between cores is reduced by 25% and the effective area increased by 25% which in combination has a dramatic impact on the coupling. A cross-section of the fiber profile is shown in Fig. 1 a). The attenuation at $\lambda = 1550$ nm is nearly identical for all input conditions at a value of 0.181 dB/km, as measured by launching into a single core and receiving the output power from all cores. The fiber cutoff wavelength of a single core was designed to be around 1340-1360 nm. The chromatic dispersion and the dispersion slope are designed to be approximately 21 ps/nm/km and 0.06 ps/nm^2/km, respectively, at $\lambda = 1550$ nm. The crosstalk between cores was measured using a depolarized source. The crosstalk between cores in the 3C-MSF is so high that the power at the output of the 60 km fiber is identical in all cores, irrespective of which core was excited at the input.

The measured linearly polarized super-modes of the 3C-MSF (upper row) and their farfield (bottom row) are shown in Fig. 1 b). The fundamental mode designated LP_{01}, since it bears common features with the LP_{01} mode of SI-FMF, is excited when all core modes have the same phase at coupling. The higher-order mode, designated by LP_{11},

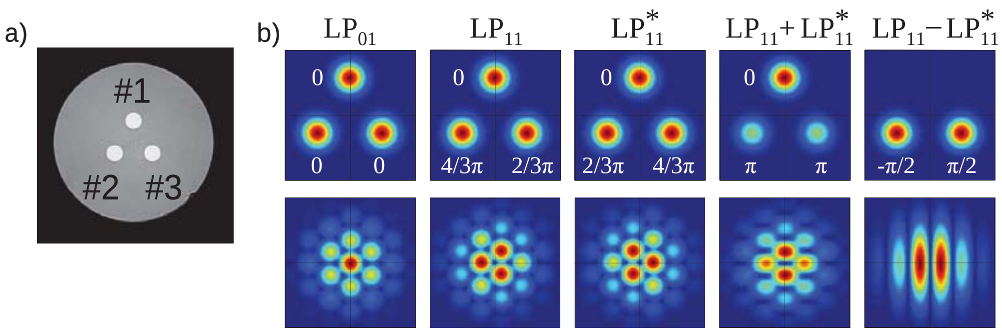

Fig. 1. a) Cross-section of the 3C-MSF b) Linearly polarized super-modes (upper row) and corresponding far-fields (bottom row) of the 3C-MSF. See text for description.

is degenerate, so multiple basis representations are possible. The LP_{11} is obtained when a continuous phase jump of $2/3\pi$ is applied to the respective core modes. The second mode designated as LP_{11}^{*} is the complex conjugated of LP_{11}. Alternatively a second basis for the LP_{11} mode is shown in column 4 and 5 of Fig.1-b). Note that in the LP representation each mode can have two orthogonal polarizations and therefore a total of 6 independent transmission channels are available for transmission as shown in the following section.

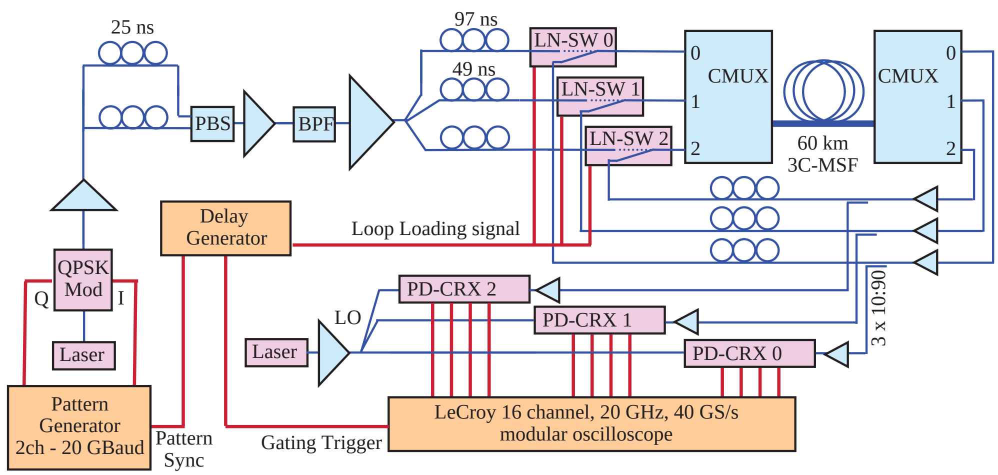

Fig. 2. Experimental set-up. QPSK-Mod: QPSK Modulator, PBS: Polarization beam splitter, BPF: Bandpass filter, LO: Local oscillator, triangles denote EDFAs.

3. Path-length-matched parallel-loop MIMO experiment

In order to study the MIMO transmission performance over long distances we built a loop experiment as shown in Fig. 2. As a light source we used an external cavity laser (ECL) with 100-kHz linewidth operated at 1560 nm, and the signal was generated by a double-nested $LiNbO_3$ Mach-Zehnder modulator, driven by a two-channel pattern generator producing two De Bruijn bit sequences (DBBS) of length 2^{12} at 20 GBd. A polarization-multiplexing stage created two polarization multiplexed copies with a delay of 25 ns, which were connected to an Erbium-doped fiber amplifier (EDFA), an optical bandpass filter (BPF) with 1.3-nm bandwidth, and an additional EDFA. Three copies of the signal with a relative delay of 49 ns and 97 ns were then generated. The delays were chosen larger than the memory of the MIMO-DSP at the receiver, and hence decorrelated the optical noise among the three spatial channels. The three PDM-QPSK signal were then connected to three $LiNbO_3$ loop switches (LN-SW).The switches are in a 2×1 configuration and inject the transmitted signals into the parallel-loops during a 2-ms loading cycle, and subsequently close the parallel-loops for 9 ms when in looping configuration. Each of the three parallel-loops consist of a concatenation of a first core coupler (CMUX), followed by a 60-km 3C-MSF, a second CMUX, an EDFA, 10:90 taps, fiber optic delays to adjust the loop length, and the LN-SW. The relative length of the individual loops had to be precisely controlled, and matched to within ± 20 mm, corresponding to a relative delay of ± 100 ps. This was required in order minimize the spread of the impulse response at the end of transmission, and therefore minimize the number of required taps in the MIMO DSP. The CMUXs which are similar to the 3-core fiber coupler presented in [10] are based on three individual collimators that are imaged on the end facet of the 3C-MSF, and has an insertion loss of 2 dB. The signals are extracted from the loop using a 10:90 coupler followed by an EDFA and feeding into three polarization-diversity coherent receivers (PD-CRX). The resulting 12 high-speed electrical signals are captured by a fully synchronized 16-channel prototype of the LeCroy LabMaster modular digital storage oscilloscope (DSO) operating at 40 GS/s with 20 GHz of bandwidth; 4 million samples are captured for each channel. A second ECL is used as a local oscillator (LO) in an intradyne configuration. The LO frequency was adjusted to within ± 20 MHz of the central frequency of the received signal. The captured signals are subsequently analyzed by MIMO DSP consisting of a network of 6×6 feed-forward equalizers (FFEs) with L taps each [6]. The FFE coefficients are adapted by a data-aided least-mean-square (LMS) estimator algorithm over the first 500,000 symbols and then switched to decision-directed LMS for the remaining symbols. The bit-error rate (BER) is evaluated over a million bits and the results for the transmission after each loop is shown in Fig. 3 a). A BER $< 10^{-3}$ can be achieved for up to 20 loops, corresponding to a distance of 1200 km.

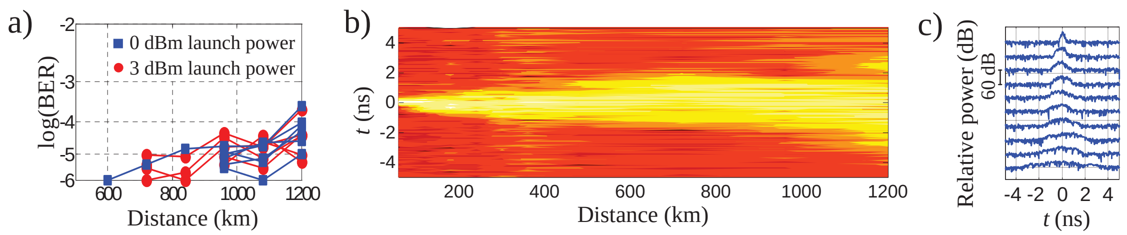

Fig. 3. a) BER as function of distance for transmission over 3C-MSF. b) Distance dependence of the squared magnitude of the impulse response in false color representation (higher magnitude is lighter colored) and c) plotted on a logarithmic scale with 60dB offset between the curves. The distances plotted starting from the top are 60, 120, 180, 240, 300, 360, 480, 720, 960, and 1200 km.

The number of required equalizer taps grows as a function of distance. After a distance of 60 km good performance is observed even for $L < 30$, whereas up to 225 taps are used at 1200 km. In order to gain a better understanding of the evolution of the impulse responses as function of the distance, we performed a channel estimation based on the least square error (LSE) estimator as described in [11]. The results are reported in Fig. 3 b) and c) where the squared magnitude of the impulse response after electronic dispersion compensation is shown as a function of the distance for one particular channel of the 6×6 impulse response matrix describing the fiber. The broadening of the impulse response is clearly visible, and a pulse width of 600 ps is measured after 60 km, growing to 5 ns after 1200 km. The pulse widening is sub-linear, but the impact of the equalizer lengths for different loop numbers has not yet been investigated. The results reported are measured with a 0 dBm launch power for each core.

In conclusion we have demonstrated the first path-length-matched parallel-loop 6×6 multiple-input multiple-output experiment showing a record distance of 1200 km over a three-core microstructured fiber using 20-Gbd-QPSK channels per mode. This experiment clearly demonstrates the that both microstructured fibers and MIMO interference cancellation are viable long-haul transmission technologies.

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