Transmission over Randomly-Coupled 4-Core Fiber in Field-Deployed Multi-Core Fiber Cable

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Abstract *We show combined SDM/WDM transmission over a deployed and cabled 4-core coupled-core fibers over distances up to 4014 km for QPSK and 2768 km for 16QAM signals. The results confirm the technical viability of coupled-core fibers in the field.*

Introduction

Space-division multiplexing (SDM) is the crucial technology for optical fiber communications to avoid a coming network capacity crunch[1], and multi-core fiber (MCF) is a promising candidate as the next-generation medium for SDM transmissions. Among various MCFs, randomly-coupled MCFs (RC-MCFs) are especially suitable for long-haul transmissions because they can achieve higher spatial density and lower attenuation, compared to uncoupled MCFs[2],[3]. Four-core RC-MCFs[2] have been shown in[4] to outperform single-mode fibers with a nominally identical core design, due to a favorable reduction of nonlinear impairments in the strong mode mixing regime[5],[6], which have been confirmed in the transmission experiments performed over RC-MCF spools in laboratories. One remaining concern is that the mode mixing could possibly become much weaker after installation because the coupling behavior in MCFs depends on fiber bends and twists. Recently, we installed an MCF cable in the field for the first time[7], and confirmed that the RC-MCFs with a proper inter-core coupling strength functions very well even in the straightened or the field-deployed loose-tube cables by measuring the spatial mode dispersion[7],[8]. However, signal transmission over field-deployed MCFs has never been reported, and the deployed MCFs have never been tested as an optical transmission medium.

In this work we show for the first time transmission over a deployed cable containing RC-MCFs confirming that the favorable performance of RC-MCFs can be obtained also in deployed fiber cables. The multi-core fiber cable is part of INCIPICT SDM transmission testbed (http://incipict.univaq.it/) and is hosted in a walkable multi-service under-ground tunnel in the historical downtown of the city of L'Aquila, in Italy.

Design and fabrication of the fiber cable

The deployed fiber cable is a 6.29-km long jelly-filled loose-tube cable with an outer diameter of 6 mm, air-blowed into a high-density polyethylene anti-rodent microduct with a 10-mm inner diameter and 12-mm outer diameter. Out of the total length of 6.29 km, 5.63 km were installed in the tunnel and the remaining 0.66 km were in the laboratory that gives access to the fibers. The cable accommodates 18 MCFs of three different types in total[7] — twelve strands of randomly-coupled four-core RC-MCFs (RC-4CF), four strands of uncoupled four-core fibers (UC-4CF), and two strands of uncoupled eight-core fibers (UC-8CF).

The RC-4CFs[7] used in this transmission experiment have four square-lattice arranged silica cores in a common 125-µm-diameter cladding. The core pitch was 25.4 ± 0.2 µm and the core-to-core coupling was weaker than for the previously reported RC-4CF[2], which had a core spacing of 20 µm. The fiber attenuation was 0.170 to 0.175 dB/km at 1550 nm. The mode field diameter and effective area averaged over the local modes of the individual cores[9] were 10.1 ± 0.2 µm and 80.9 ± 3.3 µm^2 at 1550 nm, respectively. The chromatic dispersion and slope were 19.1 $\mathrm{ps/(nm \cdot km)}$ and 0.058 $\mathrm{ps/(nm^2 \cdot km)}$ at 1550 nm. The cable cutoff wavelengths were 1.41 to 1.51 µm, which was defined as the wavelength at which the power of the higher-order

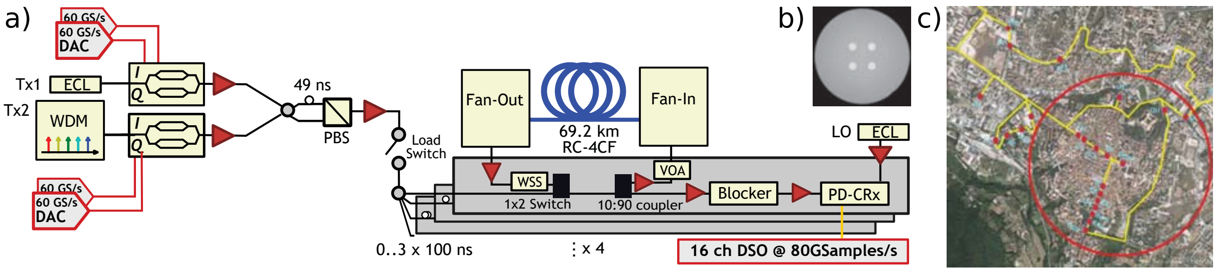

Fig. 1: a) Setup for combined WDM/SDM transmission over two spans of RC-4CF. b) Cross-section of the RC-4CF (darker represents lower refractive index). c) Map of the city of L'Aquila showing the location of the deployed cable.

modes relative to the power of the four propagation modes has been reduced to 0.1 dB, and measured with full mode excitation of the whole coupled-core structure. The signals were coupled into the cores of the RC-4CF by using a laser inscribed 3D waveguide as fan-in/fan-out (FIFO) device. By splicing 11 RC-4CFs together, a single span of 69.2 km was formed with a total insertion loss (including the FIFOs and connectors) of between 16.2 and 17.2 dB. The spatial mode dispersion of the RC-4CF was 5.7 $\mathrm{ps}/\sqrt{\mathrm{km}}$, resulting in a narrow impulse response with a width of around 200 ps after 69.2 km, as confirmed in Fig. 2a where the averaged impulse response was measured using an optical vector network analyzer (OVNA).

Transmission experiment

The experimental setup is shown in Fig. 1 and consisted of two transmitters producing 5 WDM channels spaced at 33.33 GHz and modulated at 30 Gbaud. The signals were produced by 4 independent high-speed digital-analog converters (DACs) operated at 60 GS/s, driving both in-phase and quadrature arms of two double-nested Mach-Zehnder modulators (DN-MZMs). We used 5 distributed feedback lasers (DFBs) spaced at 33.33 GHz and 2 external cavity lasers (ECLs) as light sources, where one ECL was used for the channel under test and the second as local oscillator at the receiver. The channel under test was modulated by the first DN-MZM, whereas the surrounding 4 dummy channels where modulated with an independent signal using the second DN-MZM. All modulated signals were subsequently traversing a polarization multiplexing emulation stage that introduces a delay of 50 ns between the polarizations. The resulting spectral channel plan is shown in Fig. 2b, where each letter denotes a signal modulated with a mutually independent signal. The Nyquist-shaped signals are generated using either 4 or 8 DeBruijn sequences of length 2^{16} for QPSK or 16QAM formats, respectively. The signal is further split into 4 paths and decorrelated with delay fibers with a relative delay of around 100 ns. We used 4 solid-state 1x2 switches to inject the signals into the four-fold recirculating loop and we also added a load switch to improve the extinction ratio of the injected signal. The loops consisted of 11 concatenated RC-4CFs with a total length of 69.2 km, connected to four two-stage single-mode amplifiers and four wavelength selected switches (WSS) configured as dynamic gain equalizing filters. Two laser inscribed 3D waveguides were used to interface with the 4-core fiber. Additionally, 4 variable optical attenuator (VOAs) are used to precisely control the launched power into the cores. The recirculating loop was optimized by matching all 4 single-mode path lengths to < 1 cm (corresponding to a delay < 50 ps), whereas the relative launch power was optimized to generate a minimal mode-dependent loss (MDL) at a distance of 1000 km. Subsequently, the transmitted signals were extracted from the loops using the 10% arm of four 10:90 couplers, and fed to 4 polarization-diverse coherent receivers (PD-CRXs). The resulting 16 electrical signals were then captured by a digital storage oscilloscope (DSO) operating at a 80 GS/s sampling rate. The captured signals were processed offline by first down-sampling the signals to 2 samples-per-symbol, performing chromatic dispersion and frequency-offset compensation followed by timing identification and a 8×8 MIMO processing, based on a frequency domain equalizer with 1000 symbol-spaced taps. The initial convergence of the equalizer was obtained by using the data-aided least-mean-square (LMS) algorithm, while the multi-modulus algorithm (MMA) was used afterwards. Finally, carrier-phase recovery and bit-error-rate (BER) counting were performed and the associated Q^2 factors were calculated on the average BER across all 8 spatial tributaries.

Transmission Results

The optimum launch power was first determined by transmitting a 16QAM signal at a distance

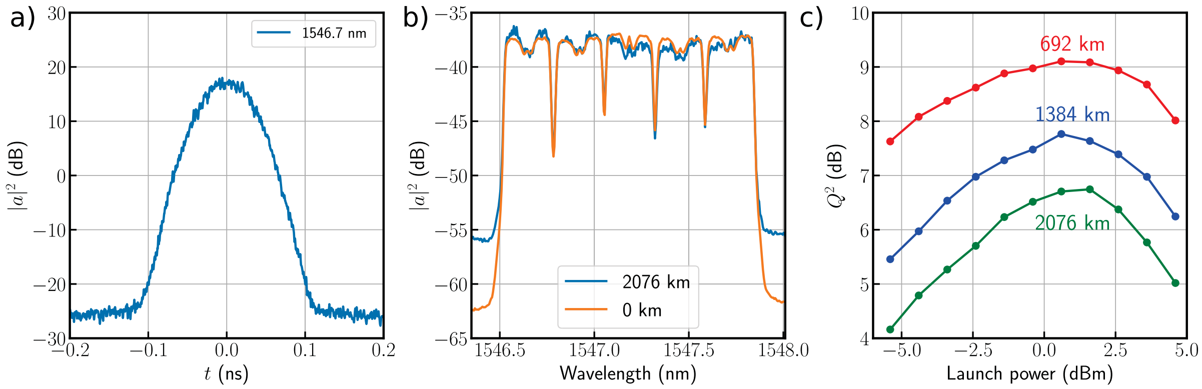

Fig. 2: a) Averaged impulse response of the 69.2-km RC-4CF span. b) Spectrum of the WDM channels before (0 km), and after 2076-km transmission. c) Q^2-factor for transmission distances of 692, 1384, and 2076 km, respectively, as function of the launch power per WDM channel, measured for 16QAM signals.

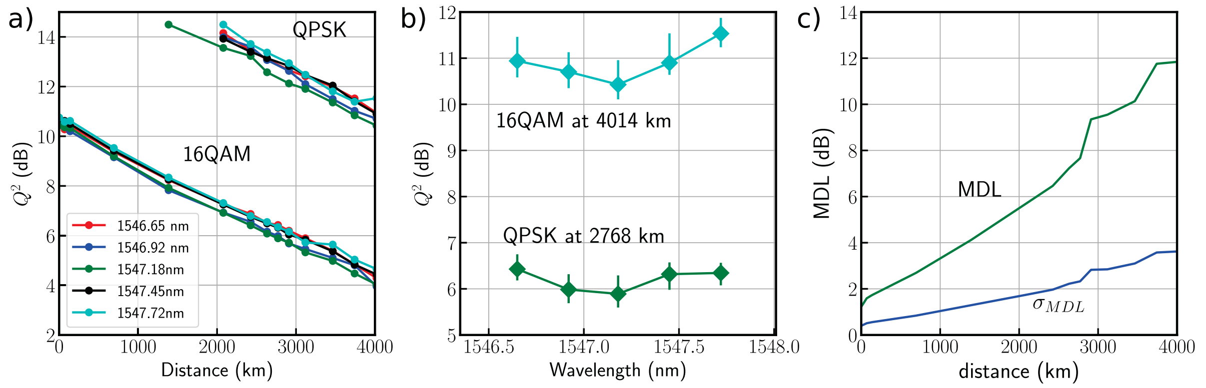

Fig. 3: a) Q^2-factor at optimum launch power as function of the distance for QPSK and 16QAM signals. b) Q^2-factors (marked as solid dot) and range of the Q^2-factors of the 8 spatial tributaries (marked as error bars) for all 5 wavelength reported for QPSK after 2768 km and 16 QAM after 4104 km. c) Mode dependent loss (MDL) and σ_{MDL} as function of the transmission distance.

of 2076 km. During the measurement all 5 WDM channels were present, but only the performance of the central channel was measured and reported in Fig. 2c. The transmission performance as function of the transmission distance is shown in Fig. 3a at optimum launch power for QPSK and 16QAM signals, and for all 5 WDM channels in a wavelength range from 1546.65 to 1547.72 nm, respectively. All Q^2 values corresponding to different wavelength channels are within 0.4 dB, showing very uniform performance, and for 16QAM signals a transmission distance of 2768 km can be recovered assuming a state-of-the-art forward-error correction (FEC) with an overhead of 20%, that requires a Q^2 value above 5.7 dB. Additionally, in Fig. 3b we show the range of the Q^2 factors of the spatial tributaries. We also investigated the evolution of the link mode-dependent loss (MDL) as a function of propagation distance. The results are shown in Fig. 3c where we report the frequency-averaged MDL, with the average being performed over a bandwidth of 30 GHz. The MDL was evaluated as the power ratio (in dB) between the least and most attenuated hyper-polarization states, $\mathrm{MDL_{dB}}(\omega) = 10\log_{10}\left\{\max_i[\lambda_i^2(\omega)]/\min_i[\lambda_i^2(\omega)]\right\}$, where by $\lambda_i(\omega)$ we denote the singular values of the link transfer matrix at the angular frequency ω. Additionally, we also evaluated the standard deviation of the singular values squared in logarithmic units $\sigma_{\mathrm{MDL}}(\omega) = \mathrm{std}_i\left\{10\log_{10}[\lambda_i^2(\omega)]\right\}$ relevant for system evaluation[10]–[12]. The values are comparable to previously reported RC-MCF experiments at similar span length, and indicate that at distances > 1000 km the MDL is dominated by contributions from the loop components.

Conclusion

Our results show that the favorable transmission properties of coupled-core fiber can be maintained even for fibers that are cabled and deployed, confirming the technical viability of coupled-core fibers.

Acknowledgment

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