Field Transmission Performance of Multi-core and Few-Mode Fibers

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Abstract: This presentation reviews accumulated knowledge on the performance of field-deployed fibers for spatially multiplexed transmission. These are multi-core and few-mode fibers deployed in the Italian city of L'Aquila as part of the INCIPICT testbed for space-division multiplexing. © 2024 The Author(s)

1. Introduction

Space division multiplexed (SDM) transmission has been at the spotlight of optical communications for the last decade, as it is considered to be the only solution to scaling the communication throughput of optical communication systems in an economically viable way [1]. The difference between transmission in parallel single-mode systems and SDM is in the fact that the latter entails some form of integration in which different lightpaths share some of the system elements, such as transceivers, optical amplifiers, network elements, and ultimately even the optical fiber itself. Integration of multiple lightpaths into a single fiber with standard cladding diameter is particularly attractive as it contains the promise of reducing the spatial occupancy of fiber cables and consequently the related costs. Moreover, in some configurations lightpath integration also yields performance benefits, such as enhanced tolerance to distortions due to Kerr effect [2]. Today's most significant efforts in the domain of SDM fiber transmission are directed towards multi-core fibers (MCFs) and few-mode fibers (FMFs) with standard 125-μm diameter, so as to ensure compliance with existing procedures and equipment for splicing, connectorization, and cable termination. While the potential of SDM transmission in these fibers has been studied intensively in laboratory settings [3], a true demonstration of its suitability for communication systems requires testing SDM systems and apparatuses in more realistic scenarios, where SDM fibers are cabled and deployed to better mimic the conditions in which systems operate in the real world.

In this paper we review knowledge accumulated in the process of deploying and operating SDM fibers in an urban environment. This initiative was put in place within project INCIPICT, which was funded by the Italian Government after the devastating earthquake that affected the city of L'Aquila on April 6, 2009. The reconstruction that started after the earthquake transformed the destroyed city into an open platform for experimenting with a variety of technologies related to the smart-city paradigm [4]. The planned SDM testbed includes two ring structures, one housed in an underground tunnel network infrastructure hosting multiple services (water, electricity, gas, telecom, etc.), and another based on ducts deployed a few tens of centimeters below the ground level. The laboratory of Optics and Photonics of INCIPICT, located in the headquarters of the University of L'Aquila, at the heart of the historical city center, gives access to the deployed fibers, as illustrated in Fig. 1. The mission of the testbed is to provide the optical communication community with a platform for testing SDM technologies at all levels, while promoting synergies between players. Currently, the shorter ring of approximately 6 km, hosted in the underground tunnel network, is complete and fully operational, and it includes both MCFs and FMFs, as described in what follows. The longer, 20-km ring, is anticipated to become operational by the end of 2024.

2. Multi-core fiber testbed: asset and field trials

The MCF testbed has been operational since June 2019. As shown in Fig. 1b, a 6.29-km jelly-filled loose-tube cable with an outer diameter of 6 mm, surrounded by a reinforced jacket and anti-rodent microduct laying on a shelf in the tunnel, was used to house 18 MCF strands of three types. These include 2 uncoupled-core (UC) 8-core fibers for O-

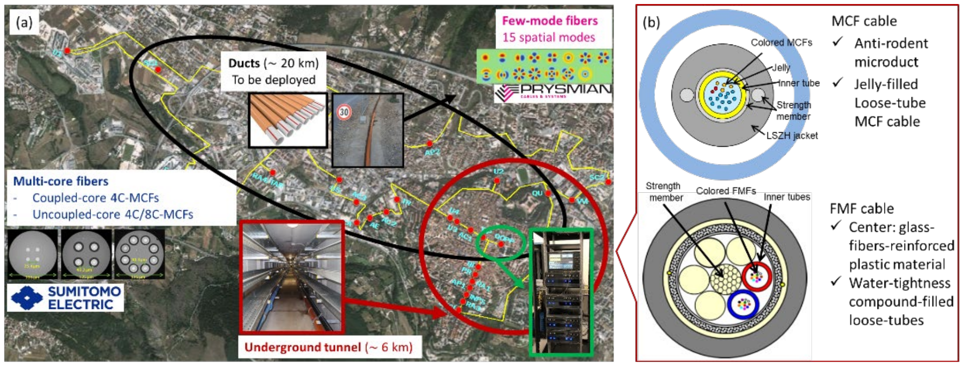

Figure 1 (a) SDM fiber testbed layout. The shorter ring of approximately six km is hosted in an underground tunnel network. The longer ring of approximately twenty km consists of traditional ducts. (b) Layout of the MCF (top) and FMF (down) cables.

band, 4 uncoupled-core 4-core fibers for O-to-L band, and 12 coupled-core (CC) 4-core fibers for C-to-L band. Out of the 12 strands of CC- MCF, 11 were spliced together to form a longer span of 69.2 km, appropriate for long-reach transmission experiments. All the UC-MCFs, as well as the isolated CC-MCF strand were terminated by means of SC-connectorized MCF pigtails on both ends, which allowed concatenating fibers of the same kind to form longer spans. Fan-in-fan-out (FIFO) devices, also terminated with SC-connectorized MCF pigtails, allow addressing the individual fiber cores. On the other hand, the 69.2-km CC-MCF span was directly spliced with the MCF pigtails of the FIFO devices [5].

The process of deploying the MCFs revealed a number of interesting features. Firstly, the fiber attenuation reduced notably from the stage of fiber spool to that of cabled fiber on a drum, with a smaller reduction in the stage of deployed cable. On the other hand, cabling increased inter-core crosstalk in the case of UC-MCFs, with negligible impact from the deployment itself. Finally, in the case of CC-MCFs, modal dispersion (MD) – a key propagation effect in SDM systems – reduced from stage to stage. In fact, a record-low MD parameter of 2.5 $\mathrm{ps}/\sqrt{\mathrm{km}}$ was measured in one of the deployed fiber strands.

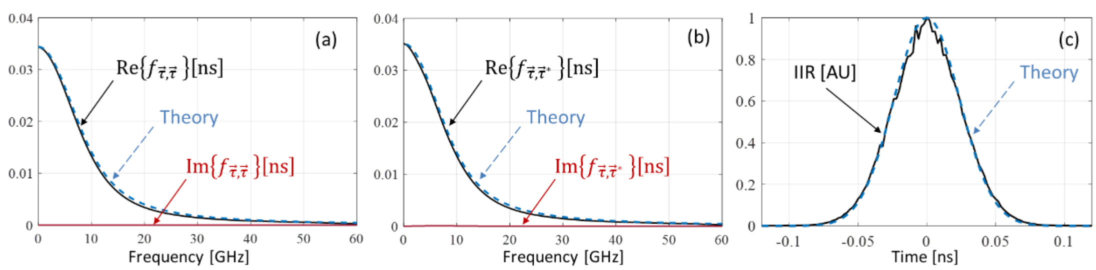

Figure 2 Real and imaginary parts of the correlation function of the complex-valued modal dispersion vector with (a) itself $f_{\bar{\tau},\bar{\tau}}$ and (b) with its complex conjugate $f_{\bar{\tau},\bar{\tau}^*}$, and (c) the fiber intensity impulse response (IIR). Solid lines refer to the data and dashed lines to the theory.

The CC-MCF link has been used to demonstrate up to 4014 km for QPSK and 2768 km for 16 QAM signaling in a recirculating-loop configuration, thereby demonstrating the technical viability of CC fiber transmission in the field, for the first time [6]. In a subsequent field trial, the same setting was used to demonstrate SDN-controlled probabilistic constellation shaping supporting multiple rates [7]. The CC-MCF was also tested in a real-time transmission experiment, showing that CC fibers are compatible with real-time DSP implementation [8]. More recently, our CC-MCFs were used to demonstrate the first meshed spatial-super-channel switching SDM network using field-deployed CC-MCFs [9]. A particularly important experiment providing insight into the frequency-dependence of random-mode coupling in CC-MCFs was reported in [10]. The data collected therein with swept-wavelength interferometry (SWI), allowed measuring the MD in the fiber, while avoiding the contribution of the terminal equipment, thereby validating a theoretical model for MD in the presence of mode-dependent loss, and shedding light on the underlying physical mechanisms [11]. Earlier attempts to do so using end-to-end transmission data were not as successful [12]. Figure 2 shows a plot of the real and imaginary parts of the correlation function of the complex-valued MD vector with itself (a) and with its complex conjugate (b), and the fiber intensity impulse response (IIR) (c), for theory (dashed lines) and data (solid lines), demonstrating the high accuracy of the theory.

A very important feature of the MCFs deployed in the tunnel is their stability, which results from the natural thermal and mechanical isolation of the tunnel itself. In [13] the phase drift between the cores of our deployed UC-4CF (arising mainly from the lab temperature fluctuations) was stabilized for tens of minutes with a relatively simple phase-locked

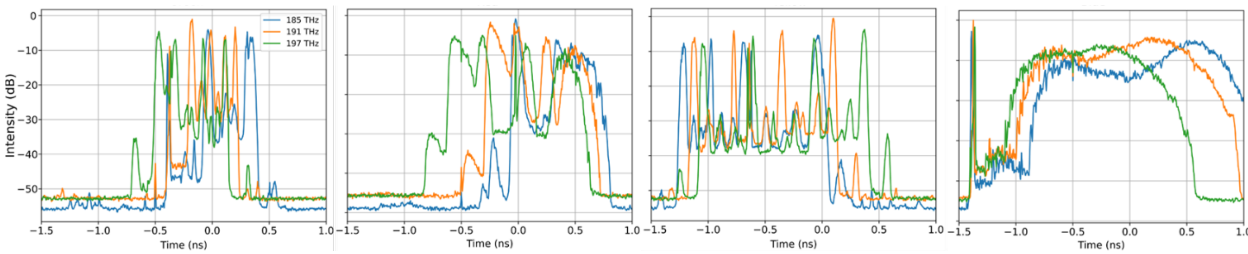

Figure 3 Intensity impulse response of the four FMF strands housed in the blue tube of the deployed FMF cable at the displayed frequencies (after [25]).

loop algorithm. This enabled the demonstration of high-dimensional QKD over 52 km of deployed UC-MCFs [14]. More recently, phase measurements of the UC-4CFs based on SWI and Digital Holography suggested that meters-long co-located fiber pigtails in the lab are less phase-stable than two cores of a full 6.29-km strand of deployed UC-4CF [15]. On the other hand, the characterization of the deployed UC-4CFs has revealed surprisingly large values of polarization-mode dispersion, first in the form of anomalous statistics of the core birefringence vectors [16], and more recently in terms of differential group delay [14]. After this problem was discovered in installed fibers, manufacturers succeeded to reduce PMD to values consistent with those of single-mode fibers [17], enabling the recently announced deployment of two-core fibers for transoceanic transmission [18].

3. Few-mode fiber testbed: asset and field trials

The FMF testbed has been operational only since July 2022, with its deployment having been delayed predominantly by the Covid-19 pandemic. As shown in Fig. 1b, the FMF cable, with an outer diameter of 13 mm, has a standard structure composed of six loose tubes with a diameter of 2.2 mm, arranged around a central strength member with a diameter of 2.4 mm. Two loose tubes (red and blue in the figure) filled with a water compound, house 4 strands of FMF each. This is a graded-index fiber with a standard 125-μm cladding diameter supporting 15 modes [19]. Multi-plane light conversion multiplexers and de-multiplexers are used to address the fiber modes, while the individual fiber strands of 6.1 km each can be used individually or spliced in concatenation, depending on the application of interest.

The first characterization experiment [20] made use of transmitted data to extract the fiber impulse response, and transmission of 15 SDM × 50 GBaud QPSK signals at 7 wavelengths across the C-band over distances up to 48.8 km was demonstrated by time multiplexing 5 coherent receiver units. The same setting was also used to demonstrate a high spatial and spectral efficiency SDM ROADM based on the deployed 15-mode fiber. Spatial super channel switching scenarios for full add&drop, full express, partial add drop, and optical bypass with a granularity of 5 Tb/s were demonstrated [21]. Transmission schemes addressing sub-groups of modes were explored in subsequent field trials. On the one hand, transmission distances from 48.8 km up to 800 km – appropriate for metropolitan networks – and spectral efficiencies from 3 bit/s/Hz to 24 bit/s/Hz, were demonstrated [22]. On the other hand, reduced-MIMO transmission, and routing of selected mode groups with low inter-group crosstalk were demonstrated for urban-network scenarios [23], [24] with over 13 Tb/s overall throughput. Notably, the characterization of the deployed FMFs still seems to require attention. Indeed, a recent field trial [25] has revealed that different fiber strands from the same preform, housed in the same loose tube, have totally different IIRs. As can be seen in Fig. 4 (after [25]), these range from multi-peak shapes, typical of weakly coupled mode groups, to bell-like shapes, that characterize strong mode coupling. Future efforts should also provide explanations for these findings.

4. Conclusions

We discussed the accumulated experience with SDM fiber systems using field-deployed MCFs and FMFs. Our findings indicate that the performance of deployed SDM fibers is compatible with communication system requirements. The ongoing deployment of more fibers in ducts, foreseen for the end of 2024, will allow testing SDM transmission in the presence of stronger coupling with the external environment.

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