SDM Fibers and Devices: Design, Manufacturing, and Applications

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Abstract: We report recent advances in the fabrication of multicore and multimode fibers, amplifiers, and devices for space division multiplexing. Low-loss and low-crosstalk fibers and devices can be achieved by carefully optimizing the fabrication processes.

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1. Introduction

Multicore fibers (MCF) are crucial fiber structures that allow for driving forward the Space Division Multiplexing (SDM) approach for data transmission in communications links by increasing the number of cores [1,2], providing multiple spatial paths within the same fiber. The number of spatial paths is directly related to the number of cores supported by the MCF. Typically, MCFs are classified into two main categories: coupled core (CC-MCF) and uncoupled core MCFs. In the first category, the cores are placed close enough to each other enabling for mire coupling [3], whereas in the second one the cores are placed far from each other to avoid power transfer between cores [4]. Usually, the design of uncoupled core MCFs includes additional trenches around each core to further reduce the crosstalk.

Recently, Multimode Fibers (MMF) have emerged as a potential candidate for long-haul data transmission [5], these MMFs have core diameter that ranges from 12 μm to 50 μm, and a cladding diameter of 125 μm which is the cladding diameter for the standard SMF. This feature enables MMFs to exploit all the benefits of the whole existent technology for SMFs processing. Additionally, MMFs reduce the challenges of fabrication, cleaving and splicing that involve the MCFs input and output components. Amplification of 6 and 10 modes supported by a MMF amplifier has been already demonstrated [6, 7]. All modes were efficiently amplified via core and cladding pump configurations with low mode dependent gain; however, differential mode group delay (DMGD) has been a limitation that needed to be addressed.

As SDM technology uses modes for each spatial channel, key complements for MCFs and MMFs are the mode multiplexers. These devices are crucial for the interrogation of each mode independently via input single mode fibers (SMF). As such, the design and fabrication of these devices together with the fiber's Fan-In Fan-Out components are very critical steps.

In this work, we present recent advances in MMF and MCF design and manufacture, together with the fabrication input/output devices to couple light into the fibers. We analyze a new MCF amplifier structure consisting of 6 coupled cores that, through a simple tapering process, is compatible and integrated within a MMF transmission link.

2. Multicore Fibers

As is known, with the appropriate core arrangement and dimensions, the crosstalk between MCF cores can be drastically reduced, therefore the fabrication of a MCF requires a strict control of the fiber structure. Small variations in the fiber dimension can lead to inaccurate fibers structures that result in MCFs with poor optical properties. The inaccuracy of the structure challenges also the splicing to FIFOs. A simple way to reduce the crosstalk in a MCF is to place the cores far from each other, as is shown in Fig. 1(a). However, this comes with the disadvantage of limiting the number of cores that the MCF can support. A greater number of cores and larger core-to-core distance is directly related to the final cladding diameter. Increasing the number of cores and the core-to-core distance will increase inherently the fiber diameter. Such fiber can be considered unsuitable for long haul transmission links, compared to SMF standard dimensions. With the proper selection of the core refractive index, i.e., introducing air gaps between cores [8] or surrounding the core with a trench for better mode confinement, the core-to core separation can be significantly reduced, allowing to incorporate a larger number of cores in a single MCF (depicted in Fig.1(b)), and reducing the cladding diameter while maintaining low crosstalk values.

The MCFs discussed in this work consist of hexagonal arrangements of single mode cores. As illustrated in Fig. 1(a) the pitch between cores is 45 μm, enabling the positioning of seven single mode cores in a fiber with a cladding diameter of 125 μm. As result of this large core-to core separation, a crosstalk below -50 dB was measured between cores. The number of cores can be increased by placing a second ring of single mode cores surrounding the first ring. Fig. 1(b) shows the microscope image of a fabricated 19-core MCF. This fiber has 180 μm cladding diameter and a core-to-core distance of 33 μm. As we can see, increasing the number of cores results in a gain of fiber size with a slight degradation of the crosstalk between cores. The fabricated 7 and 19-core MCF have a Δn of 5.07×10^{-3} and -10.08×10^{-3} for core and trench, respectively, and were drawn in home.

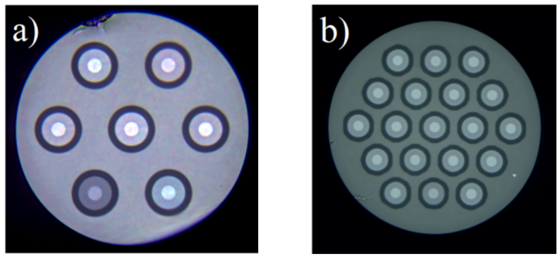

Fig.1 Homemade MCF (a) 7-core with large core-to-core pitch, and (b) a 19-core fiber with short core-to-core pitch.

3. Multimode Fibers

MMFs with graded index core are more suitable SDM applications. Latest studies have demonstrated that graded index MMF can be designed to achieve low attenuation loss and low DMGD [5]. Similarly to the case of MCFs that utilizes a trench surrounding each core to reduce the crosstalk, graded index MMFs are designed with a trench around its core to reduce bend losses. Furthermore, the well-engineered parabolic profile of the refractive index, i.e. the appropriated effective index difference between the highest order guided modes and the radiation of the leaky modes, allows to improve the MMFs DMGD and microbending loss. As such, many other MMF characteristics, have been investigated in order to optimize the graded index MMF performance for long distance fiber communications applications.

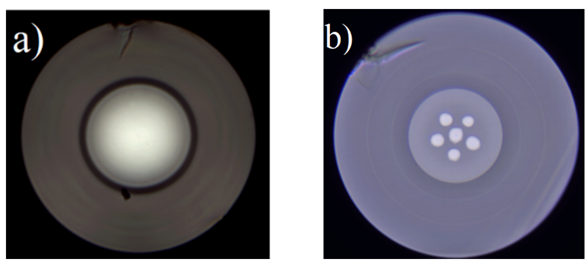

Fig. 2 Microscope images of a (a) Graded index MMF, and (b) coupled core Er-doped MCF.

.4. Multicore Fiber Amplifier

For uncoupled core MCFs the coupling between cores is a drawback but for same purposes it can be used beneficially, e.g. to produce strong random mixing between them. The coupled core arrangement concept helps to minimize the group delay because the signal for each core propagates nearly equal. Furthermore, in a fiber amplifier, it has the advantage to reduce the mode dependent gain (MDG) due to the fact that it has a more evenly pump distribution among all the cores.

To get a fiber amplifier with such characteristics and make it compatible with transmission MMFs, a reduced cladding Er-doped MCF was fabricated. The fiber consists of 6 Er-doped cores with $\Delta n = 16 \times 10^{-3}$ and diameter of 5 μm each, the core-to-core distance between the external ring of cores is 7 μm, while the separation between the central and the surrounding core is 8 μm. The background material that supports the cores is pure silica glass that is in fact surrounded by a fluorine doped external jacket with Δn = -8.2x10-3. Fig. 2(b) shows a microscope image of the fabricated Er-doped MCF where the diameter of the pure silica background is 35 μm. The fabricated fiber is coated with a low refractive index polymer in order to achieve a large numerical aperture (NA) for a suitable multimode pump confinement when the amplifier is designed for cladding pump configuration. A fiber with these core dimensions can operate under the coupled core regime, providing all afore mentioned benefits that mixing the signal modes across all the supported cores can produce. Thus, the fiber is ready to be applied as an Er-doped coupled core amplifier.

The compatibility of this Er-doped MCF with transmission MMF is carried out by performing a small ratio adiabatic taper in the Er-doped MCF. In this way, what we bring the Er-doped MMF from the coupled core regime into the multimode regime. By tapering the Er-doped fiber, we are not only reducing the core and cladding diameter, but we are also reducing the core-to-core separation. Smaller Er-doped core diameters, and reduced core to core separations fall into the multimode regime. The light leaking from each core, and the small space between them produce interference giving rise to supermodes that are propagated in a new multimode core, which is basically composed by the pure silica region and whose cladding is given by the fluorinated section of the MCF. In this way, we drive from MCF to a MMF that can get easily compatible and applicable in MMF high-capacity long distance transmission systems.

When adiabatically tapering the Er-doped MCF in both ends, and splicing it with an input and output FMF, we are transitioning from MMF modes to CC-MCF modes and back to MMF modes within a low-loss regime, paying especial attention to the high precision that this process requires. The MMF - CC-MCF - MMF is illustrated in the Fig. 3. It can be noticed that the tapered coupled-core Er doped fiber actually acts as a low-loss mode convertor from MMF modes to coupled-core fiber modes and vice versa, allowing for the suitable integration of CC-MCF amplifiers in MMF transmission systems.

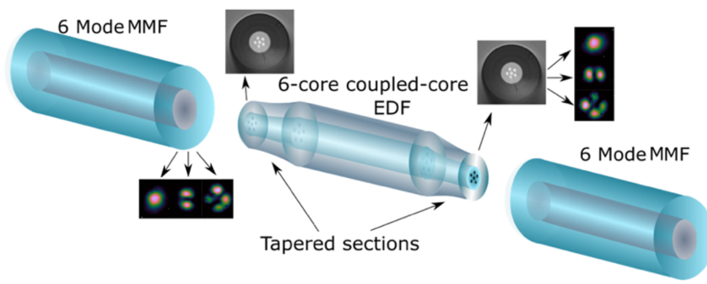

Fig. 3 Microscope images of the input/output GRIN fiber used for the FIFO fabrication.

Key elements for the study of SDM communication systems are the mode multiplexers. These components enable for the characterization of each independent spatial path through the SDM transmission system. An all-fiber mode multiplexer that has been demonstrated as reliable, easy to handle, and low loss device is the commonly known as Mode Selective Photonic Lantern (MSPL) [9]. MSPLs consist, essentially, of a bundle of input SMFs with dissimilar core sizes inserted in a fluorinated silica tube that is adiabatically tapered to fibers size. The resultant structure is a MMF whose core is constituted by the contribution of all SMF claddings, and the new cladding is given by the fluorinated silica tube. Thus, the input modes of the SMF evolves in a set of LP modes given by the achieved MMF. The number of LP modes provided by the MSPL is equal to the number of input fibers. Since the fabrication principle for the MSPLs is quite similar to the afore mentioned tapering process of the Er-doped MCF, in both cases the obtained fibers are designed to be easily spliced to other SDM fibers.

5. Conclusions

In summary, we reviewed some examples of low loss fibers, and all-fiber components suitable for SDM transmission systems. Examples of MCFs using arrays with 7-core and 19-core are provided. We discussed that higher capacity SDM systems are possible with the adequate design of the fiber structures, because this simplifies, for example, the fabrication or the splicing process, among other requirements that handling the fiber implies. The discussed SDM fiber and components are appropriate for transmissions links, because low DSP complexity is required, therefore, cost, as well as the energy consumption of the fiber link can be reduced.

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