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Multi-mode capacity enhancement with PBG fibre

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Mode conversion technologies for few mode fibers

January 2015

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contents

1. Introduction

Space-division multiplexing (SDM) using the cores in multi-core fiber (MCF) and the modes in few-mode fiber (FMF) have been explored to avert the capacity bottleneck of the existing single-mode fiber (SMF) optical networks limited by fiber nonlinear effects[1]. A series of state-of-the-art demonstrations have proven SDM's feasibility, including 140.7Tb/s transmission[2] over a 7-core MCF of 7326km, which is a record SDM transmission distance, as well as mode division multiplexing (MDM), combined with wavelength division multiplexing (WDM) transmission over a single-core 6-mode FMF with a spectral efficiency of 32bit/s/Hz[3]. This spectral efficiency is almost 3 times larger than the maximum capacity in theory that an SMF link can offer. Recently, MDM transmission was verified over a conventional multi-mode fiber (MMF)[4], which further enhances the possibility for the practical applications of SDM.

Coupling into and out of the modes in an FMF's single core is very challenging and often requires bulky free-space imaging optics. Femto-second laser-inscribed 3-dimensional-waveguide (3DW) technology can write compact waveguides into a transparent substrate[5] and enables coupling between an SMF array on a 1D pitch to an FMF with a 2-dimensional mode pattern. 3DW technology is ideal to build "photonic-lantern" FMF spatial multiplexers (SMUX) that merge many single mode waveguides into one waveguide that supports many modes[6]. A good SMUX for FMF must minimize the mode-dependent loss (MDL) and insertion loss (IL).

In this paper, we report two packaged 6-spatial mode 3DW photonic-lantern SMUXes coupled to an SMF array on one end and an FMF array on the other. Packaging requires that the super-mode sizes at the output of the 3DW are the same as in the FMF. Unfortunately, it is hard to fabricate uniform and low-loss laser-inscribed waveguides with enough index contrast over a large enough area. For the 3DW SMUX to support 6 super-modes, its dimension must increase and produce modes that are 40% larger than the FMF modes. As a consequence, butt coupling the SMUX to FMF results in a large MDL of 12dB; if external imaging optics are used the MDL can be reduced to 5dB[7]. Here, we enlarge the FMF modes through up-tapering such that they match the 3DW modes. This enables us to co-package two 3DW based SMUXes to two FMFs and to 12 SMFs, as illustrated in Fig. 1.

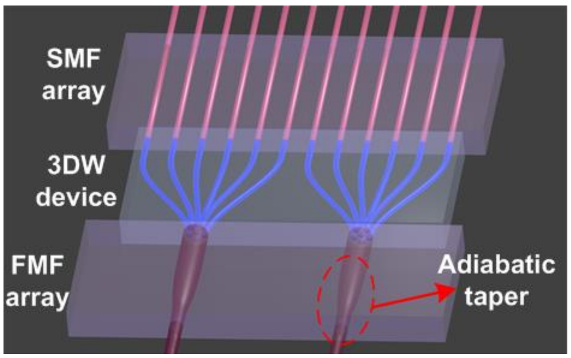

Fig. 1: Sketch of the fully-packaged dual-fiber SMUX with up-tapered 6-mode FMFs

2 Photonic Lantern 3DW SMUX

Laser-inscribed waveguides were investigated as early as 1996[5]. Currently, laser-inscribed single-mode waveguides at 1550nm with low coupling loss to SMF and propagation losses (0.1dB/cm) have been realized. However, refractive index changes induced by the laser inscription are constrained to a small volume. Some results with high index contrast (i.e., $\Delta n > 6 \times 10^{-3}$) were presented through an additional fabrication process[8,9], but the uniformity and the scattering of the waveguides were not thoroughly discussed. 3DW devices with low Δn can work properly for MCF coupling due to the single-mode operation, whereas for FMF, a larger Δn is required for direct coupling between a 3DW SMUX and FMF, especially in the case with a large number of modes.

Fig. 2(a) and (b) show a few-mode 3DW structure approximated by multiple cores that support 3 and 6 super-modes, respectively. *d* is the waveguide diameter and *r* is the outer ring radius. The mode field diameters (MFDs) of a graded-index 3-mode[10] or 6-mode[3] FMF with 1% index contrast are approximately 10μm to 15μm. To obtain a low MDL, the 3DW modes must match the FMF modes.

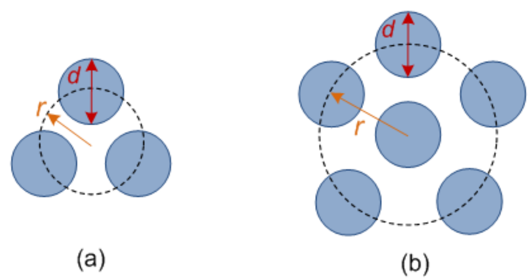

Fig. 2: Waveguide spatial arrangements for supporting (a) 3- and (b) 6-spatial modes.

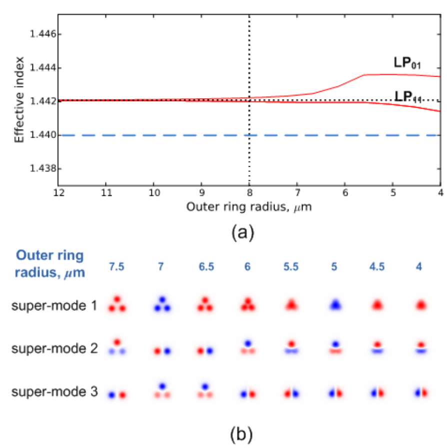

Fig. 3: The evolution of (a) effective indices of super-modes and (b) mode fields with a decreasing outer ring radius *r* for a 3-core photonic lantern.

Fig. 3(a) and (b) shows the modes and their effective indices for 3 cores that are being merged. The simulation solved the scalar wave equation at 1550nm wavelength, with a substrate index of n=1.44, refractive index contrast of $\Delta n = 3.5 \times 10^{-3}$, and *d*=4$\mu$m. Fig. 4 shows that the 3 super-modes are guided for all *r* cases and evolve into the LP_{01} and LP_{11} modes.

However, as the number of cores increases, the higher order modes cannot be supported. Fig. 4

shows the simulation results for the 6-core photonic lantern structure. In order to have a similar MFD to the 6-mode fiber, *r* needs to be lower than 5*μ*m. However, when *r* is below 6*μ*m the higher-order modes are evanescent modes and cut-off, as shown in Fig. 4(b). This means that *r* has to be kept larger than 6*μ*m in order to support the LP_{21} and LP_{02} modes. In this case, the few-mode core can guide the 6 modes but with a larger MFD. In order to minimize the MDL due to the mode profile mismatch, free space imaging optics has been employed[7].

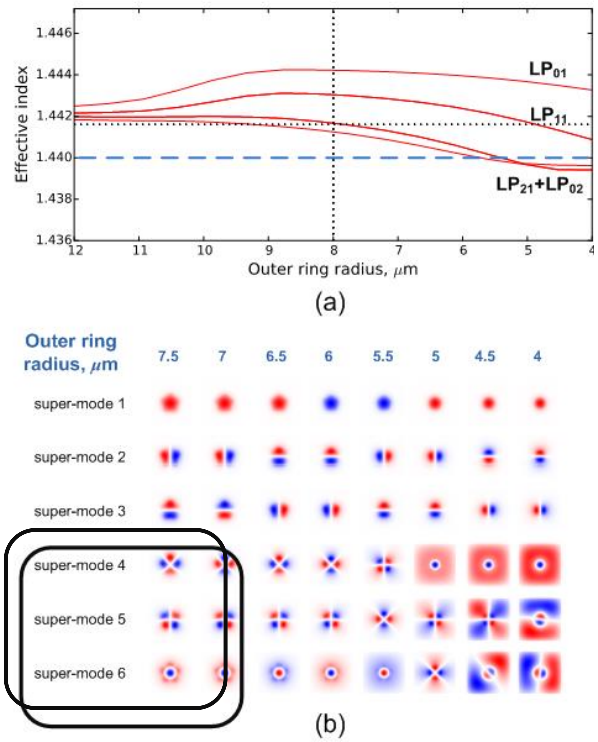

Fig. 4: The evolution of (a) effective indices of super-modes and (b) mode fields with a decreasing outer ring radius *r* for a 6-core photonic lantern.

3 MDL measurements

We propose to use adiabatically up-tapered FMFs to match the larger super-modes guided by the 3DW devices due to the low Δn. Up-tapering is done by a CO_2 laser fiber-fusion tapering station and MDL is measured using a swept-wavelength interferometer[11]. The fabricated 3DW based 6-mode SMUX includes two identical 6-core photonic lanterns with *r*=7.5*μ*m and *d*=6*μ*m. The FMF has a standard cladding of 125*μ*m.

Fig. 5 shows the measured MDL when butt-coupling into and out of three FMFs with different up-tapered sizes over a frequency span of 1800GHz, centered at 193.4THz. MDL for a single device is measured in reflection mode using the facet of the FMF as a reflection[7]. The interface between the SMUX and the FMF is passed twice in the reflection measurement, therefore, the induced MDL of one mode coupler is approximately half of what is measured. With 40% up-tapering (175*μ*m cladding) the double-pass MDL is reduced to 5dB from 12dB (result without tapering). Additionally, 3.8dB IL is achieved for the up-tapered 175*μ*m cladding case.

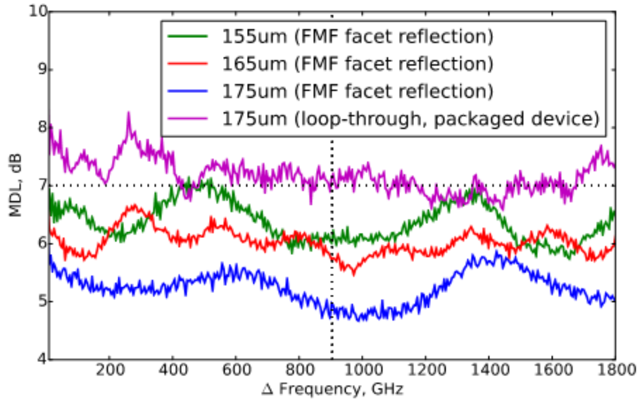

Fig. 5: Measured MDL results for FMFs with different up-tapered sizes by facet reflection and the packaged dual-channel device by loop-through. (Without up-tapering, MDL is >12dB.)

4 Fully-packaged 3DW device

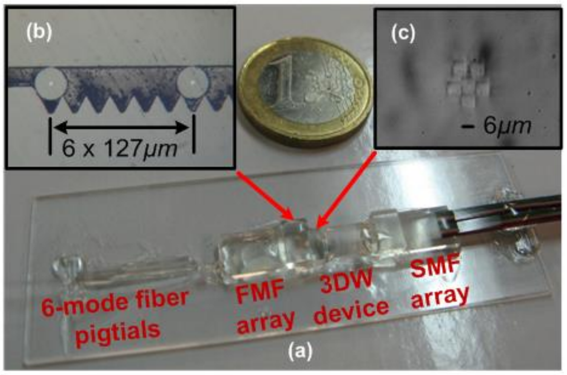

Fig. 6: (a) Picture of the packaged 3DW device; microscope images of (b) the up-tapered FMF array facet and (c) the 3DW facet with merged 6 cores.

The fully-packaged dual-FMF 3DW SMUX is with two 6-core photonic lantern structures, which can be used as mode multiplexer and demultiplexer, respectively. Two adiabatically up-tapered 6-mode FMFs with optimal cladding of 175μm are positioned and assembled in a standard V-groove with a pitch of 127μm. SMF array, 3DW device and FMF array are glued together using UV curing epoxy. Fig. 6(a) shows the picture of the packaged 3DW device, which has a link IL less than 8dB and a double-pass MDL around 7dB, as shown in Fig. 5. The MDL is measured with a loop-through FMF in which the two photonic lanterns are linked by a 50m FMF. The loop-through MDL is 2dB worse than that of a single 6-core SMUX measured in the reflection case. The increase is probably from incorrect distance between two up-tapered FMFs. Fig. 6(b) and (c) show the microscope images of the FMF array facet and 3DW photonic lantern facet, respectively. The V-groove array (designed for 125μm fiber) does not hold the 175μm up-tapered FMF and is one source of distance error.

5 References

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