A Fully-packaged 3D-waveguide based Dual-fiber Spatial-multiplexer with Up-tapered 6-mode Fiber Pigtails

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Abstract We demonstrated a fully-packaged dual-fiber 3D-waveguide (3DW) spatial multiplexer, which has 7dB mode-dependent loss (MDL) and <8dB insertion loss in a multiplexer/demultiplexer pair. Mode profile mismatch between the 3DW device and few-mode fiber (FMF) is solved by up-tapering FMF side.

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\textsuperscript{1}. A series of state-of-the-art demonstrations have proven SDM’s feasibility, including 140.7Tb/s transmission\textsuperscript{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\textsuperscript{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)\textsuperscript{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\textsuperscript{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\textsuperscript{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\textsuperscript{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.](image)

Photonic Lantern 3DW SMUX

Laser-inscribed waveguides were investigated as early as 1996\textsuperscript{5}. Currently, laser-inscribed single-mode waveguides at 1550nm with low coupling loss to SMF and propagation losses (0.1 dB/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\textsuperscript{5,9}, but the uniformity and the scattering of the waveguides...
were not thoroughly discussed. 3DW devices with low $\Delta n$ can work properly for MCF coupling due to the single-mode operation, whereas for FMF, a larger $\Delta n$ 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 or 6-mode 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.](image)

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 $d=4μm$. 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 5μm. However, when $r$ is below 6μm 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 6μm 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.

![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.](image)

**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 $\Delta n$. Up-tapering is done by a CO$_2$ laser fiber-fusion tapering station and MDL is measured using a swept-wavelength interferometer. The fabricated 3DW based 6-mode SMUX includes two identical 6-core photonic lanterns with $r=7.5μm$ and $d=6μm$. The FMF has a standard cladding of 125μm.

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. 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 (175µm cladding) the double-pass MDL is reduced to 5dB from 12dB (result without tapering). Additionally, 3.8dB IL is achieved for the up-tapered 175µm cladding case.

Conclusions

We successfully co-packaged two 3DW photonic-lantern SMUXes to an SMF array and an up-tapered FMF array and obtained a double-pass MDL of 7dB and IL<8dB. Up-tapering the FMF enlarged the FMF modes such that they match the larger modes of the low-index contrast of the 3DW SMUX. Up-tapering of the FMF side removes many constraints from 3DW design. The packaged device performance is comparable to the optimized SMUXes using external imaging optics.

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References