Mode-Group-Selective Photonic Lantern Using Graded-Index Multimode Fibers

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Abstract: We fabricate mode-group-selective photonic lanterns using multimode graded-index fibers. The use of the multimode graded-index fibers in the taper can significantly relax the adiabaticity requirement in comparison with using single-mode fibers.

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1. Introduction

Recently, few mode fibers (FMFs) and multicore fibers (MCFs) have been explored to overcome the capacity limit of single mode fibers (SMFs) [1]. For FMF transmission, a multiple-input multiple-output (MIMO) coherent system has been employed, which consists of an array of transmitters, a spatial multiplexer (SMUX), a FMF, a spatial demultiplexer (SDeMUX), an array of coherent receivers, and MIMO processing. SMUXes and SDeMUXes are key components for space-division multiplexing (SDM). The photonic lantern (PL) (Fig.1) is a promising candidate for spatial S(De)MUXes in SDM as they provide low insertion loss, low mode dependent loss and broad bandwidth [2-4]. PLs can be made to be mode-selective if the multiple input/output fibers are different. Mode-selective PLs can find applications for SDM transmission in FMFs with low mode crosstalk such as time-division multiplexed (TDM) passive optical networks (PON) [5]. For long-distance SDM transmission in low-crosstalk FMFs, mode-selective PLs can also be used to compensate differential modal group delay (DMGD) to reduce multiple-input multiple-output (MIMO) complexity [6]. Because degenerate modes in FMFs will couple to each other, mode-group-selective (MGS) PLs are adequate for the above-mentioned applications.

We report here a new method for fabricating MGS-PLs. The key innovation is the use of multimode instead of single-mode fibers, in particular graded-index multimode fibers (GI-MMFs), as input/output fibers for multiplexing/demultiplexing, which alleviates adiabatic requirement and achieves high mode selectivity. To demonstrate the advantages of using GI-MMFs, we compare experimentally the performance of two MGS-PLs with the same tapering length, one using the GI-MMFs and the other using SMFs.

2. Rationale for Employing Graded-Index MMF

The ability for the PL to scale to more mode groups is very desirable. MGS-PLs for two mode groups demonstrated so far require a very long taper to be adiabatic and the adiabatic tapering length is estimated to increase as $N^2$ for $N$ spatial modes [4]. Adiabaticity criterion is expressed as [4]:

$$\left| \frac{2\pi}{(\beta_1 - \beta_2)} \int_0^1 \left( \Psi_1 \frac{\partial \Psi_2}{\partial \rho} \right) dA \right| \ll 1$$

where $\Psi_1$ and $\Psi_2$ are the normalized field distribution of the local modes that are likely to couple to each other, $\beta_1$ and $\beta_2$ are their respective propagation constants, $\rho$ is the local core radius. The first term of Eq. (1) dictates that the tapering rate $\frac{d \rho}{dz}$ is proportional to the differences in the propagation constants of the two modes. The second terms of Eq. (1) suggests that mode profiles that change slowly as the fiber is tapered will lead to smaller crosstalk.

We propose to use GI-MMFs to satisfy the adiabaticity requirement via both terms of Eq. (1). The first term is related to the selection of dissimilar GI-MMFs in building a MGS-PL. The selection rules are two-fold. First, the difference of propagation constants between fundamental modes corresponding to the output mode groups should be as large as possible to make adiabatic tapering more robust. The other factor is the effective index of the modes do not cross or interact with each other during the taper. To be more specific, the effective index of the fundamental mode of
each GI-MMF must be larger than that of any higher order mode. Fig.2 illustrates input fibers that meet those selection rules for a MGS-PL that supports three mode groups. The packing of GI-MMFs is shown in Fig. 2(a). The input fiber at the center is a 22μm-core-diameter GI-MMF for exciting the $L_{P_{11}}$ output mode group 1, the two 20μm-core-diameter GI-MMFs excite the $L_{P_{11}}$ mode group 2 and the three 15μm-core-diameter GI-MMFs excite the three nearly-degenerate $L_{P_{11}} + L_{P_{9}}$ mode group 3. In Fig.2 (b), the effective indexes of 3 mode groups of interest (1-black, 2-blue, 3-blue) and other higher-order mode groups (red) which become radiative modes during the taper are plotted as functions of the taper ratio. It is noted that the effective index of the higher-order modes is smaller than that of any of the fundamental modes of the 6 dissimilar fibers, ensuring that no resonant coupling occurs between a high-order mode from one input fiber to a fundamental mode of another fiber.

![Image](72x514 to 543x604)

Fig.2: (a) Six-mode lantern index profile with 3 types of dissimilar cores (1, 2 and 3). (b) Propagation constants of the modes at different stages of the taper. (c) Refractive index profile of GI fiber and step-index fiber. (d) Effective index of the fundamental mode in a taper.

The second term is determined by how fast the mode field diameter changes. Fig.2 (d) shows the effective areas of the fundamental mode of step-index fiber and GI fiber with $\alpha = 2$. In the simulation, the index profile is shown in Fig.2 (c) and the index contrast in simulation is 1%. From Fig.2 (d), the effective area of the GI-fiber changes much slower than the step-index fiber. Therefore, GI MMF can more readily satisfy the adiabaticity requirement. Furthermore, GI MMFs can have very low splice loss to the standard SMF since the effective area of GI MMFs can match that of the standard SMF (shown in black line).

### 3. Experimental Results

Two different MGS-PLs supporting two mode groups were fabricated with exactly the same fabrication process and taper length. One was made by using dissimilar SMFs and the other with dissimilar GI-MMFs. The lantern end facets and output intensity profiles of the two lanterns are shown in Fig.3 (a-d). The output intensity profiles for the $L_{P_{11}}$ mode group of the MGS-PL using dissimilar SMFs, shown in Fig. 3(b), do not show high mode-group selectivity as one of the $L_{P_{11}}$ output intensity profiles has a significant residual $L_{P_{9}}$ component. However, for the MGS-PL using dissimilar GI-MMFs, the mode selectivity is high. The output intensity profiles for the $L_{P_{11}}$ mode groups, shown in Fig.3 (d), are ring-like representing linear combination of only the two $L_{P_{11}}$ modes. A MGS-PL for three mode groups was fabricated using GI-MMFs as well. Fig.4 (a, b) show the lantern end facet and output intensity profiles of MGS-PLs supporting three mode groups using GI-MMFs. High mode group selectivity can be observed.

![Image](72x162 to 539x281)

Fig. 3 (a) End facet and (b) near field mode profile of 2-MGS-PL using dissimilar SMFs. (c) end facet, (d) near field mode profile and (e) mode selectivity characterization of MGS-PL for two mode groups using dissimilar GI-MMFs.

To characterize the performance of MGS-PLs using GI-MMFs, we butt coupled the MGS-PLs to a 50 μm GI-MMFs and measured the insertion loss and mode selectivity. Insertion loss was measured to be less than 0.6 dB for both MGS PLs for two and three mode groups. To characterize mode selectivity we use a swept-wavelength interferometer (SWI) with spatial-diversity operating in reflection mode to measure the transfer matrix across the entire C-band [7]. The system measurement is from the SMF inputs fusion spliced to the input GI-MMFs, through the
PL, 50-meter output GI-MMF, cleaved facet of the output GI-MMF, then back through 50-meter GI-MMF, PL and to the SMF. The 50-m GI-MMF introduces modal group delays by which the mode groups can be separated. The MGS-PL acts both as a multiplexer and a demultiplexer in this measurement. For the MGS-PL supporting two mode group, the transfer matrix contains 36 elements (2 polarizations × 3 spatial modes). Fig.3 (e) shows summations of the elements to capture the signal and the crosstalk. The 1-1 cell shows the clean excitation of the \( LP_{01} \) mode with suppression of the HOMs. The 2-2 cell shows excitation of the \( LP_{11} \) modes with 40-dB rejection of the \( LP_{21} \) mode, and about 20-dB rejection of the \( LP_{21} \) modes. The 2-1 cell shows the total crosstalk between groups, and is 20-dB smaller than the signals. These measurements show that MGS-PL supporting two mode groups has a 20-dB mode selectivity into GI-MMF.

![System crosstalk matrix element of MSG-PL for three mode groups using dissimilar GI-MMF's](image)

Fig 4. (a) end facet, (b) near-field profile and (c) mode selectivity characterization of MGS-PL for three mode groups using dissimilar GI-MMFs.

For MGS-PL supporting 3 mode groups, the method to measure the transfer function is the same. The transfer matrix is much more complex and contains 144 elements (12×12). We reduce the matrix to highlight the signal power and crosstalk. From Fig. 4 (c), the 1-1 cell shows excitation of only the \( LP_{01} \) with 40-dB suppression of each of the HOMs. The 2-2 cell shows excitation of the \( LP_{11} \) modes with 40-dB rejection of the \( LP_{01} \) mode and HOMs, and 20-dB rejection of the \( LP_{21} \) modes. The 3-3 cell shows excitation of the \( LP_{21} \) modes with 35-dB rejection of the \( LP_{01} \) mode and HOMs, and 15-dB rejection of the \( LP_{11} \) modes. The crosstalk cells show 20-dB, 10-dB and 7-dB rejection for measured groups 1, 2 and 3 respectively.

### 4. Conclusions

We demonstrate the use of GI-MMFs to form MGS-PLs, which are shown to have better performance than those using SFMs. With relaxed adiabaticity requirement offered by this approach, fabrication of MGS-PLs for more mode groups becomes possible.

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