Mode Group Diversity Multiplexing over Graded-Index Polymer Optical Fiber Links

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Graded-index polymer optical fiber (GI-POF) is considered a suitable medium for in-house networks. This is due to the flexibility and large core of GI-POF that facilitate installation. The possibility of using mode group diversity multiplexing (MGDM) over GI-POF is investigated. The basic ideas apply, however, mode mixing poses a strong restriction. Furthermore, although the flexibility of the polymer material is advantageous concerning installation, experimental results indicate that it makes GI-POF sensitive to bending and pressing that can seriously affect the near-field pattern at its output end. This influences the transmission matrix of an MGDM system and hence its performance.

Introduction

Mode group diversity multiplexing (MGDM) is a technique that creates parallel, independent communication channels, transparent to the signal format, over a multimode fiber (MMF), using groups of the propagating spatial modes. MGDM uses intensity modulation, direct detection, selective excitation and detection of the mode groups and electronic processing to cancel cross-talk among the channels [1, 2]. In principle, MGDM can be applied over both silica- and polymer-based MMF. Silica-based graded-index (GI) MMF was used in previous investigation on the design of an MGDM link [2]. In this paper, polymethylmethacrylate (PMMA)-based GI polymer optical fiber (POF) is considered.

GI-POF is commonly based on the PMMA material [1, 3]. Perfluorinated (PF)-polymer-based GI-POF has more recently emerged as a low loss, high bandwidth transmission medium [4]. GI-POF has typically large core diameter and numerical aperture (NA), although no definite standards exist. For PMMA-based GI-POF, the core radius (a) is usually 250 μm and the NA is 0.29, while for PF-based GI-POF, $a = 60$ μm and NA $=$ 0.171. The large radius and NA of PMMA-based GI-POF gives its special advantages related to the ease of coupling and relaxed alignment. This makes PMMA-based GI-POF a very interesting option for in-house connections.

Selective excitation of PMMA-based GI-POF with an SMF

In MGDM over GI-MMF, each mode group yields a different near-field pattern (NFP) at the output end of the GI-MMF [1, 2]. To investigate the possibility of MGDM transmission over PMMA-based GI-POF, an experimental investigation of the NFP at the output end of PMMA-based GI-POF under selective excitation with a radially offset single-mode fiber (SMF) has been carried out. A 635 nm Fabry-Pérot multi-quantum-well laser diode was used to excite a perdeuterated PMMA GI-POF with $a \approx 200$ μm and NA $= 0.274$ [5].

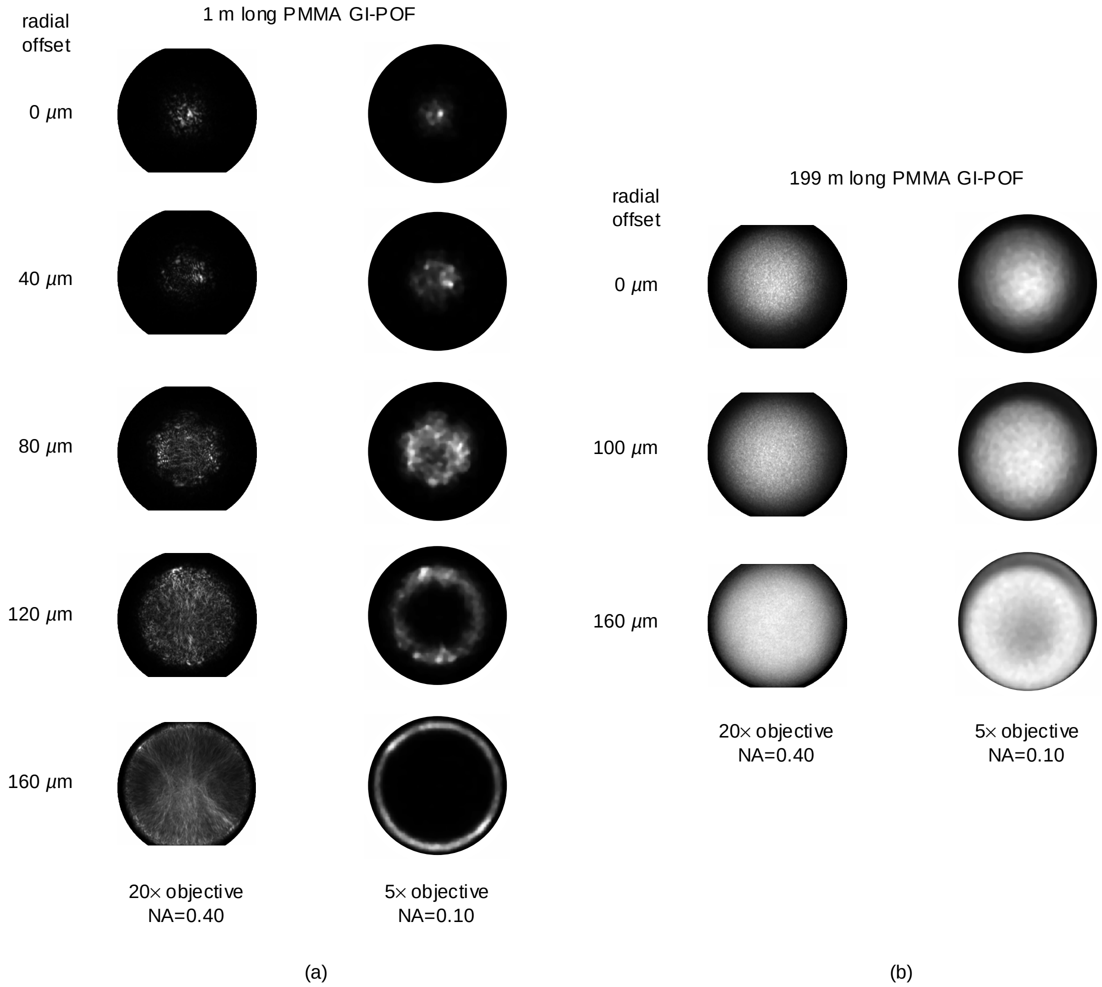

Figure 1: Observed NFPs at the output end of a (a) 1 m (b) 199 m long PMMA-based GI-POF under selective excitation with an SMF, at 635 nm wavelength. Each row corresponds to a different radial offset of the input SMF and each column to a different microscope objective. The 20× magnified core exceeds the dimensions of the CCD camera. Mode-selective spatial filtering is achieved with the 5×, 0.10-NA microscope objective [6].

The laser is pigtailed with an SMF with a mode field diameter of 4.2 μm and NA $= 0.12$, at 635 nm. A microscope projected the NFP at the output face of the GI-POF onto a CCD camera. An image of the projected pattern was grabbed with video processing software. Two microscope objectives were used, a 20×, 0.40-NA one gathering all the light at the output end of the GI-POF and a 5×, 0.10-NA one achieving mode-selective spatial filtering (MSSF), its NA being lower than the NA of the GI-POF [6].

The observed images are shown in Figs. 1(a) and 1(b) for the cases of a 1 m and a 199 m long GI-POF, respectively. The results obtained with the 1 m long GI-POF are very similar to the ones obtained with silica-based GI-MMF [2]. In particular, the NFP has a disk-like shape, with its radius depending on the radial offset of the input SMF. This disk-like pattern turns into a doughnut-like pattern when MSSF is applied [6]. The NFP at the output face of the 199 m long GI-POF exhibits similar characteristics, although indicating at the same time that mode mixing is very strong. The dependence of the NFP on the radial offset of the input SMF is much weaker than in the case of the 1 m

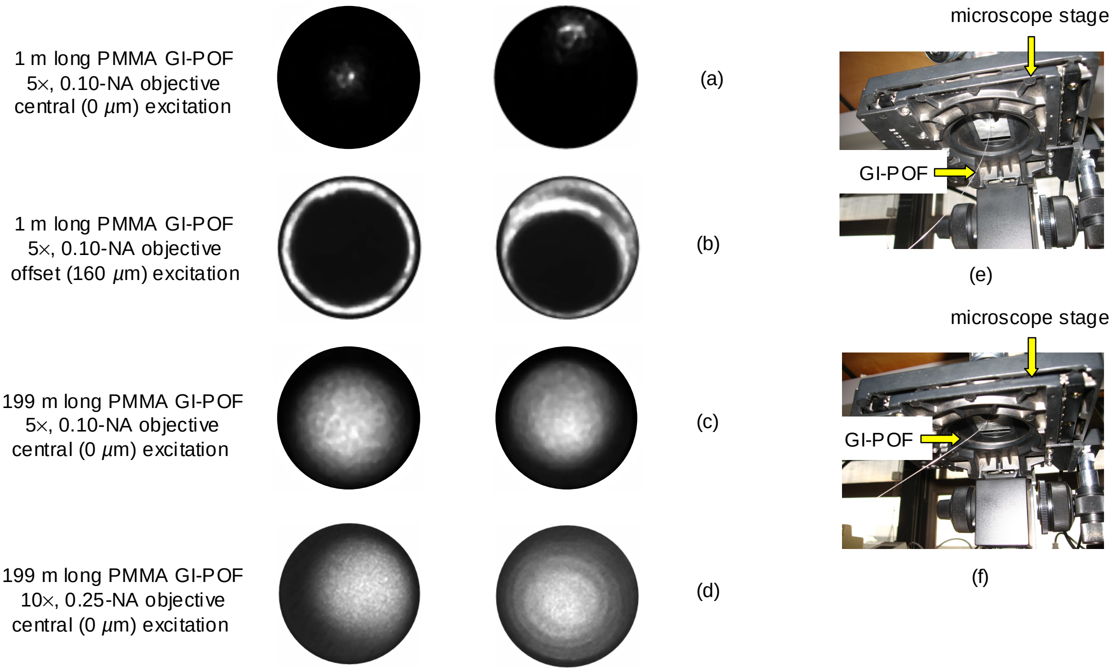

Figure 2: Experimental results showing changes in the observed NFP at the output end of a (a,b) 1 m and (c,d) 199 m long PMMA-based GI-POF, at 635 nm wavelength. In all images, except the right one in (d), the changes in the observed NFP are due to a bend at the output end of the GI-POF, such as the one shown in (f). In (e) a straight placement of the output end of the GI-POF is illustrated. The right image in (d) is after the GI-POF is pressed with the fingers at around 30 cm from its output end. Similar results were obtained with the 20×, 0.40-NA microscope objective.

long GI-POF. In this case as well, MSSF affects the observed images and improves the spatial separation of the patterns. It should be noted that doughnut-like patterns at the output of PMMA-based GI-POFs have been previously reported [1, 3]. These patterns were referred to as the NFP, without any indication to spatial filtering similar to MSSF. It would be interesting to further investigate this difference.

The experimental results of Fig. 1 show that it is possible to use MGDM transmission over PMMA-based GI-POF. Unfortunately, though, unlike the case of silica-based GI-MMF [2], the transmission matrix and the number of channels would depend on the length of the GI-POF. This is because mode mixing is very strong in GI-POF. For the two PMMA-based GI-POFs used, it appears from Fig. 1 that a five (two) channel system would be possible with the 1 m (199 m) long GI-POF. This dependence on the GI-POF length complicates the specification of the geometrical parameters of an MGDM multi/demultiplexer similarly to the case of silica-based GI-MMF [2]. Mode mixing is not the sole factor that limits the maximum length of PMMA-based GI-POF in MGDM transmission. Attenuation is another very significant factor. The GI-POF sample under investigation has a loss of less than 100 dB/km at 635 nm [5].

The two PMMA-based GI-POFs under test were bare, i.e. there was no coating around their cladding, and their ends were not connectorized. Bending of the GI-POFs at a distance comparable to 1 cm from their output end changed the NFP. Typical patterns, for central excitation, are shown in Figs. 2(a), 2(c) and 2(d). When the GI-POF output end is in a straight position [Fig. 2(e)], the overall NFP is confined within a disk which is concentric with the fiber core. However, bending of the GI-POF output end [Fig. 2(f)] moves the overall NFP, which does not remain concentric with the fiber core. This is very clear in Fig. 2(a) that corresponds to the 1 m long GI-POF. It is also shown in Fig. 2(c) and the left picture of Fig. 2(d) for the 199 m long GI-POF. For offset launch, differentiation of the NFP also occurred for similar bending close to the GI-POF output end [Fig. 2(b)]. At the same time, when similar bending was forced at a larger distance from the GI-POF end, only the speckle pattern changed, while the overall NFP remained stable. Therefore it seems reasonable to assume that this bending did not really cause strong mode mixing. It may, though, have caused macroscopic deformations in the refractive index profile that changed the path of light locally. Since the effect becomes visible when the bending occurs very close to the GI-POF output end, using a connector at this end may reduce or even eliminate this problem. Finally, the right picture of Fig. 2(d) shows the NFP, for central excitation, when the 199 m long GI-POF is pressed with the fingers at a distance of about 30 cm from its output end. The induced change in the NFP indicates that the applied stress causes mode mixing. The observed sensitivity of the NFP at the output end of PMMA-based GI-POF, as shown in Fig. 2, has not been reported before and it would deserve further investigation.

Conclusions

In MGDM over GI-MMF, each mode group yields a different NFP. Due to strong mode mixing, the overall NFP at the output end of PMMA-based GI-POF under selective excitation with a radially offset SMF is strongly dependent on the length of the GI-POF. Further, although the large core size and flexibility of PMMA-based GI-POF offer advantages with respect to installation, the overall NFP is sensitive to bending that occurs very close to the output end of the GI-POF and to pressing of the GI-POF. These factors may cause practical difficulties for a reliable MGDM system with PMMA-based GI-POF.

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