All fiber $N \times N$ fused tapered plastic optical fiber (POF) power splitters for photodynamic therapy applications

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We fabricated various types of plastic optical fiber (POF) fused taper $N \times N$ splitters ($N = 4, 6, 8, 10, 20, 30,$ and 60). Inert gas was electrically heated and injected through a nozzle to provide an oxygen-free hot zone to process PMMA POF fused taper. The devices showed unique splitting characteristic to provide a dominant direct output port along with $N - 1$ weakly coupled output ports, which might have a significant potential in photodynamic therapy applications.

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1. Introduction

Medical treatments, such as photodynamic therapy (PDT) [1], that use photochemical processes between laser and photosensitizer have attracted huge attention in recent years. A photosensitizer excited by laser light of specific wavelength, usually from visible to near-infrared, is chemically activated to carry out a role killing specific target cells and it can destroy tumor by exposing laser beam on the area to be treated.

In order to guide laser beam with minimum loss, optical fiber has been regarded as the most suitable device. Particularly plastic optical fiber (POF) can be a strong candidate due to its versatile capabilities; guiding visible light, bio-compatible composition, and cost effectiveness. Especially in order to treat internal organs, fiber is an unavoidable component to guide the light to a specific location within our body. Current laser beam delivery through optical fibers is based on very simple scheme: one output port per one input port. In practical applications where multipoint laser delivery is necessary, it would be highly desirable to have a type of power splitter or coupler that provides multiple output ports per one input port or multiple output ports per multiple input ports.

Various types of POF splitter have been reported such as Y-shaped micro-optic type [2], side polished type [3], diffused light type [4] and the active splitter using a liquid crystal in the intermediate coupling region [5]. However these devices are not appropriate in in vivo applications due to their structural design limitations.

In this paper, we report a new method to fabricate fused taper POF using heated gas injection burner technique, and optical characteristics of fabricated $N \times N$ POF splitters ($N = 4, 6, 8, 10, 20, 30,$ and 60) are investigated for PDT applications.

2. Experiment results

Fig. 1a shows the structure of POF used in our experiment. Core consists of a PMMA and cladding is consisted of a fluorinated polymer to form a lower refractive index than that of a core. The index profile is depicted in Fig. 1b. The refractive index of the core is 1.49 and that of the cladding is 1.40, which forms a step index profile. The cladding diameter is about 250 $\mu$m and core diameter is about 240 $\mu$m.

In order to fabricate a POF splitter, we need to provide a heat source to satisfy both fusion of multiple strands of POF and elongation of the fused segment forming a taper structure. Conventional heating method is not acceptable with POF splitter fabrication due to the following reasons. PMMA based POF has a glass transition temperature around 115 °C [6], above which POF begins to melt.
Fig. 1. (a) Structure of POF. (b) Refractive index profile.

Fig. 2. Schematic of fabrication system.

Fig. 3. Measurement set up. He-Ne laser at 633 nm was used as a light source. All of output power from $N \times N$ POF splitters were measured by using an optical power meter.

Fig. 4. The power of output port. (a) $4 \times 4$, (b) $8 \times 8$, (c) $20 \times 20$, and (d) $60 \times 60$. 
with an abrupt elasticity change within a very narrow temperature range. Furthermore, chemical reactions with O₂ in an elevated temperature will disturb POF chemical structure. In order to control the temperature precisely and deactivate O₂ related chemical reactions, we used an inert gas stream heater to form a hot zone for fusion and tapering of POFs. The schematic of fabrication system is shown in Fig. 2. When POFs are held in fiber holders, they are heated near the center by the N₂ gas jet stream that is injected through an electrically heated nozzle. As the POF strands are heated they are pulled and rotated simultaneously by motorized stages to provide a consistent condition for fusion and tapering process.

Various conditions were set up for \( N / C_2 \) in terms of hot zone temperature, pulling speed, rotation speed, and initial POF strand twisting. For these splitters the coupling ratios were investigated and Fig. 3 shows the measurement setup. As a light source, He–Ne laser at 633 nm was launched into one of input ports and all of output powers from \( N / C_2 \) POF splitters were measured by using an optical power meter. The results are shown in Fig. 4a–d. The photographs of fused tapered region of fabricated \( 8 \times 8 \) splitter and output ports are shown in Fig. 5.

In these experiments, the direct output port has maximum power and the rest of the ports have relatively low but uniformly distributed power, which indicates the coupling between the direct port and the surrounding ports is weak but uniform. The ratios between the direct port output power and the coupled port output power in \( N \times N \) splitters were about 6:1, 10:1, 5:1, 11:1, 40:1, 50:1, 50:1 for \( N = 4, 6, 8, 10, 20, 30, \text{ and } 60 \), respectively.

We also calculated excess loss which is defined by

\[
\text{Excess loss} = 10 \times \log\left( \frac{P_{\text{direct}} + P_{\text{coupled}}}{P_{\text{input}}} \right).
\]

The values of excess loss are 8.09, 8.01, 4.98, and 11.7 dB, respectively for each \( N = 4, 8, 20, \text{ and } 60 \). These excess losses are attributed to radiation mode loss in the fused taper region and can be further improved with optimal process conditions.

These coupling characteristics would not be appropriate in conventional optical communication applications but can be efficiently applied to PDT. For example the direct output port could be aligned to the center of cancerous target cell at a high laser power dose, while other coupled output ports can illuminate nearby tissues potentially malignant, at a low power dose in order to maximize the PDT efficiency. The characteristics in Fig. 4 would fit this purpose well and actual PDT applications are being investigated by the authors.

3. Conclusion

POF \( N \times N \) fused tapered splitters were successfully fabricated by using a novel inert N₂ gas stream heater. Fabricated splitters showed unique characteristics with one direct output port along with \( N - 1 \) uniformly coupled output port, which can be applied in photodynamic therapy application to effectively control the laser dose around the target cancerous areas.

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