Simulation and experimental research on polymer fiber mode selection polished coupler

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Multimode dispersion is the main obstacle for high bandwidth in multimode optical fiber (MMF) communication system. Mode selection is an effective method to oppress multimode dispersion. We propose and investigate a kind of polymer optical fiber polished coupler. Beam propagation method (BPM) is employed to calculate the coupling coefficient of transmission modes in MMF coupler, and an output pattern from coupling branch is obtained. Analysis and experiment show that this coupler can select certain modes by changing polished depth, contact area, and intersection angle of two branches, which means that the device can be employed both as a mode selector and a sensor. In addition, simulation shows that five times bandwidth enhancement may be realized by selecting modes with the polymer fiber polished coupler.

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Multimode optical fiber (MMF) is widely used in many fields. Compared with single mode fiber (SMF), polymer multimode fiber (PMMF) has many advantages, such as large core, low price, high flexibility, etc.. PMMF is well-known in sensor and communication applications. Now, it has played an important role in in-house networks system[1]. In this system, PMMF provides lower cost and more convenience compared to traditional silica optical fiber (SOF). However, the high transmission loss and low bandwidth of the PMMF limit its development in communication system. Nowadays the low loss PMMF (about 0.05 dB/m for 580 nm) has appeared and could decrease the transmission loss, while the low bandwidth caused by high differential mode delay (DMD)[2−4] is still a difficulty.

The core diameter of common PMMF is about 1 mm. This kind of fiber contains millions of stable transmission modes, accompanying with high multimode dispersion. DMD is induced by velocity difference of the modes (multimode dispersion). To keep the advantages of large mode area fiber, mode selection is an acceptable way to enhance the bandwidth. Therefore implementing the mode division multiplexing to reduce the amount of modes is necessary in PMMF applications. Adopting graded-index polymer optical fibers (GI-POF) is another way to reduce DMD, which was first reported by Koike *et al.* in 1990[5]. Yet GI-POF cannot be fabricated easily and the core is more expensive than that of step-index POF (SI-POF), which implies that it has limited applications. Thus selecting the modes in MMF becomes the key technique. By employing offset-launch techniques[6], mode scramblers (bending the fiber to leak the high order modes)[7] or the connection between hollow optical fiber (HOF) and MMF[8], mode selection can be achieved, yet not perfectly, with disadvantages such as fabrication problems, high insertion loss, connection difficulty between SMF and MMF.

In current techniques, the SOF coupler, which is formed by putting two cladding-polished fibers closely together, makes the light couple from the direct-branch to the coupling-branch by evanescent field. This device has been used for decades, but this kind of coupler was only employed as power splitter[9]. We propose a kind of polymer fiber polished coupler and describe its structure. Experiment and simulation have shown that by changing polished depth, contact area and angle, certain modes can be selected. In this way, the bandwidth can be enhanced in network systems.

Figure 1 shows the schematic diagram of polymer polished coupler: PMMF is polished in chucking appliance to expose the core of the fiber, which has a double-taper surface. The polished coupler is made with SI-POF (HP HFBR-RUS100), of which the core diameter is 0.98 mm. Matching oil ($n = 1.491$) is applied between the surfaces. The polished depth is 0.2 mm. The chucking appliances of both branches contact closely. Light source is a 532-nm laser diode (LD). In our experiments, the chucking appliances are set with two dimension of freedom, allowing adjustment of rotation or translation for the two branches, thus selecting the desired modes.

It is necessary to describe the fabrication steps of the chucking appliance, as shown in Fig. 2. The chucking appliance consists of two tightly fitted plates, which are connected by a threaded connector. Each of the plate is polished and indented with a notch to fit the polymer

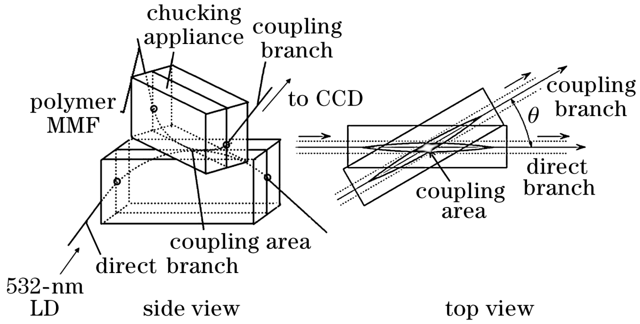

Fig. 1. Schematic diagram for polymer polished coupler. The angle θ and contact area can be changed to select certain modes.

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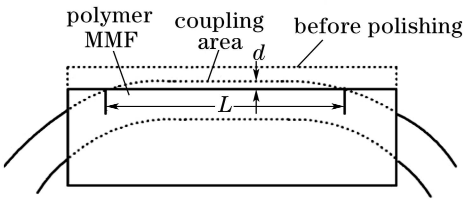


Fig. 2. Structure of the chucking appliance, in which L is polished length and d is polished depth.

fiber. Then surfaces of the plates are polished together with the fiber in it, so cladding and core are partially removed. The advantages of the device are: (1) Mode selection is performed within the coupling process of the polymer fiber simultaneously, and no additional components are needed. (2) Low requirements for precision. Polishing and drilling are the only manufactural mechanisms it needs. (3) High efficiency is performed by leading different modes into several fibers via multiple fiber arms.

Stable modes, from the basic one to cut-off mode, transmit in direct branch. When the light transmits through the coupler, some will leak out to the coupling-branch and transmit as stable transmission modes because of the destruction of the waveguide structure by polishing. Some of the modes are selected while light reflects repeatedly in the coupling area. We infer that the number of selected modes will decrease with the increase of θ and the decrease of the coupling area.

A series of experiments using the described device were carried out for implementing mode selection. The refractive indexes of core and cladding are 1.492 and 1.417, respectively. The polished length (L) is 20 mm, with polished depth (d) of 0.2 mm. The output from the LD was directly coupled into the PMMF. A charge coupled device (CCD) camera was set in front of the end face of the coupling branch or direct branch with the distance of 5 mm. We changed the output power from the LD and then measured the output power of the direct and coupling branches, as shown in Fig. 3. Two branches were placed in parallel and the polished surfaces were tightly pressed together. The slope is 0.28, i.e., about 20% power launched into the direct branch leaks out to the coupling branch.

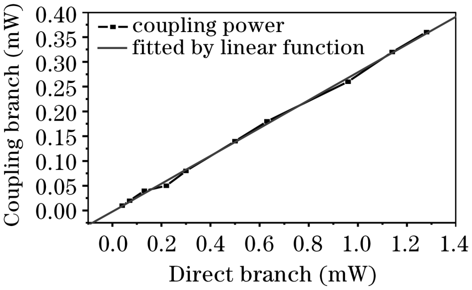


Fig. 3. Output power from coupling branch versus that of direct branch with the slope of 0.28.

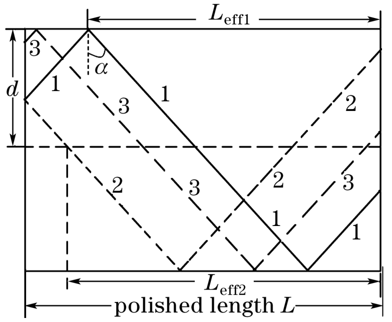


Fig. 4. Schematic diagram for our simulation method.

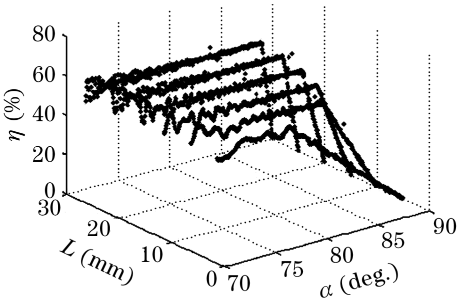


Fig. 5. Coupling coefficient η of different modes, while L and α are the polished length and the incidence angle, respectively.

Because the polished depth is deep, power will not transmit via evanescent wave coupling[9]. Therefore it is not suitable to employ the coupled-wave theory. We use the beam propagation method (BPM) to calculate the coupling coefficient η, considering the meridian beams and assuming that the two branches are placed in parallel. Whether a certain mode (with a certain incidence angle α) can couple into the coupling branch only depends on its incidence point and the orientation. As shown in Fig. 4, the meridian beams can reflect several times in the coupling area. In three beams shown in this figure, only beam 1 can be coupled to the other branch in these beams with the same incidence angle, though beam 2 has the same incidence point. By changing the incidence point and angle α, we can get the η-α curves group in Fig. 5.

This method could be described in detail as below. We divide the diameter into N part to indicate different incident point. A certain mode can be assumed to be a group of ray, which launches into the fiber at different points. $L_{\rm eff}$ is calculated from polishing length L and fiber diameter, like $L_{\rm eff1}$ and $L_{\rm eff2}$ shown in Fig. 4, thus rays with different orientation are considered different, even they launch at the same point. By combining incident point and $L_{\rm eff}$, we can judge whether the ray is coupled to the other branch. Supposing M units of the ray are to be coupled, we know that $\eta = M/(2N)$ for each mode (at one incident point there exist two orientations, so N is doubled). Next by changing incident angle α, we can plot the transmission-incident angle curve.

From Fig. 5, it is obvious that coupling coefficients η of high order modes with low α are larger than that of the basic mode, which means that this coupler can be employed as a mode-selector. Moreover, the shorter the polished length is, the fewer modes are selected. Yet too short L may induce low coupling coefficient and fabrication difficulty.

By analyzing the η-α curves and considering the core radius influence in POF (we cannot suppose the output surface as a point because the distance of the emitting surface to the CCD camera is only 5 times of the core diameter), the intensity distribution of output pattern is shown in Fig. 6. The experimental results are in agreement with numerical simulation. Additionally, SI-POF with this coupler has the same output pattern as HOF, which can be adopted to enhance the telecommunication quality[8]. Through the simulation in Ref. [10], five times of bandwidth enhancement may be realized by selecting modes with the polished coupler. As observed in the experiments, changing the relative position and angle θ of two branches, different modes were selected from the overfilled fiber. The output patterns from coupling branch are shown in Fig. 7 when θ varies from 0° to 30°. The received power changes simultaneously. These experiments show that the POF coupler could be employed not only as a mode selector to enhance the bandwidth, but also as an angle or position sensor. In addition, the POF coupler has been employed as multiplexer in a visible light wavelength division multiplexing system recently[11].

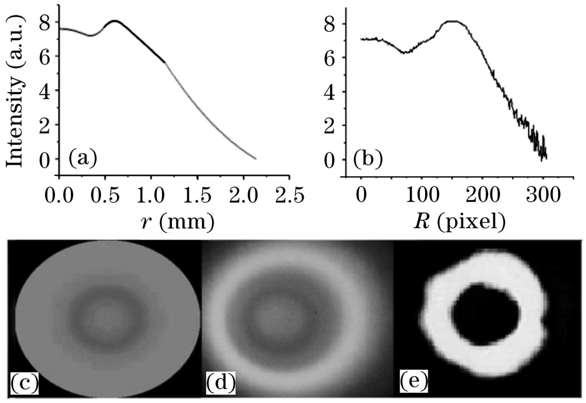
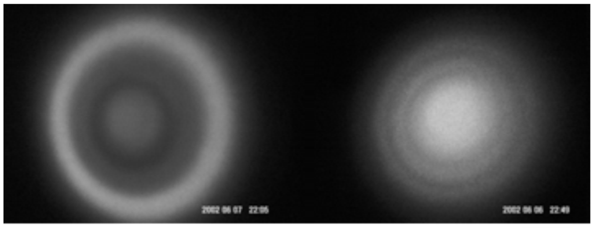


Fig. 6. Output patterns of coupling branch when two branches are placed in parallel. (a), (c) The light spots by simulation and experiment respectively; (b), (d) the radial intensity distributions corresponding to the light spot; (e) the output pattern of the HOF fiber reported in Ref. [8].



(a) (b)

Fig. 7. Output patterns of the coupler. (a) Two branches are placed in parallel; (b) two branches have a θ of 30°.

In conclusion, this paper proposes a SI-POF polished coupler. This technique can select several modes from an overfilled multimode SI-POF by using a coupler instead of the offset-launch technique, mode scramblers or HOF fiber. With the mode selection of this coupler, five times bandwidth enhancement may be realized. The experimental results are in agreement with numerical simulation and analysis, which indicates that this technique could be employed to improve the in-house networks system to a higher level. Furthermore, it can be applied in sensor field on account of its sensitivity for position and angle changes.

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