In-phase mode selection of 18-core photonic crystal fiber based on Talbot resonator*

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An effective mode selection is important for the multi-core photonic crystal fiber (PCF) to obtain good output. Talbot cavity is popular to lock the in-phase mode, but few satisfactory experimental results have been reported. In this paper, a dual-Talbot cavity with reflected mirrors on each side of PCF is designed to lock the in-phase mode. The design gains the advantage of in-phase mode against out-of-phase mode. What's more, it can weaken the influence brought by the imperfect end facet of the fiber. The corresponding theoretical analyses and the experiment are taken. The experimental results suggest that the dual-Talbot cavity improves the capacity of mode selection.

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The output of the multi-core photonic crystal fiber (PCF) would be a superposition mode[1,2]. Many methods, including the Talbot cavity, self-Fourier transform resonator and all fiber approach[3-7], have been proposed for locking the in-phase mode. Talbot cavity is popular to achieve the goal, but few satisfactory experiment researches have been reported. It's suggested that the theory of the Talbot cavity still needs to improve, and the dual-Talbot cavity is proposed in this paper.

In this paper, another mirror is put on the output side of the fiber in the single-Talbot cavity to make up the dual-Talbot cavity. The dual-Talbot cavity can gain the self-coupling coefficients of the in-phase mode and enhance the mode selection ability.

The multi-core PCF is pumped by a 980 nm laser diode (LD). An aspheric lens coupling system couples the pump light into the inner cladding of PCF. The Talbot mirror I is a high-reflection (HR) mirror at 1030–1060 nm, while the mirror II acting as the output mirror has 70% reflectivity in the same wavelength range. A screen is located at a distance away from the mirror II to receive the far-field image of output. The experimental setup is shown in Fig.1.

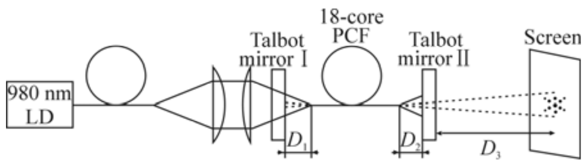

Fig.1 Schematic diagram of the experimental setup

The fiber used in this experiment is the Yb-doped 18-core PCF. The end facet of PCF is illustrated in Fig.2. The cores are arranged in hexagonal structure, where the core diameter is about 16 μm, and the air hole diameter is about 4.1 μm, so the air-hole pitch is approximately 10.1 μm, and the inner cladding diameter is 230 μm. The numerical aperture (NA) at 980 nm is greater than 0.6, while the NA at 1060 nm is 0.04 approximately.

The oscillation light propagating along the 18 cores can contact with each other to emit 18 eigenmodes (supermodes)[8-11]. Through the Fresnel diffraction integral and the results of the near-field distribution calculated by COMSOL multiphysics, the far-field intensity distributions are obtained when D_3 in Fig.1 is 8000 μm. Some supermodes with n=1, 11, 17 and 18 are shown in Fig.3. The in-phase mode is six-fold symmetry as shown in Fig.3(d).

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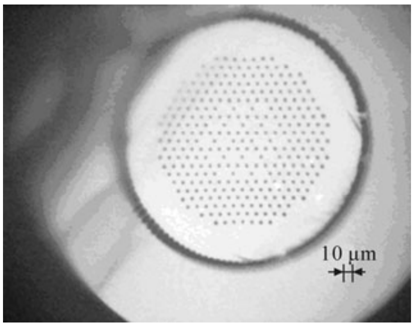
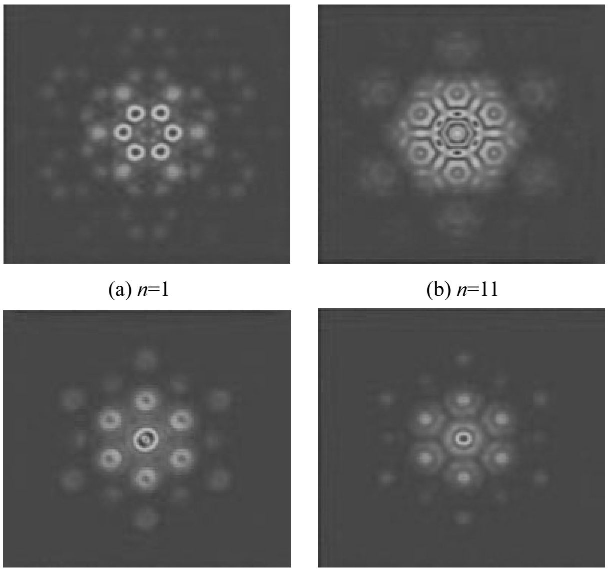


Fig.2 Image of the end facet of the Yb-doped 18-core PCF



(a) n=1 (b) n=11

(c) n=17 (d) n=18

Fig.3 Several far-field intensity distributions

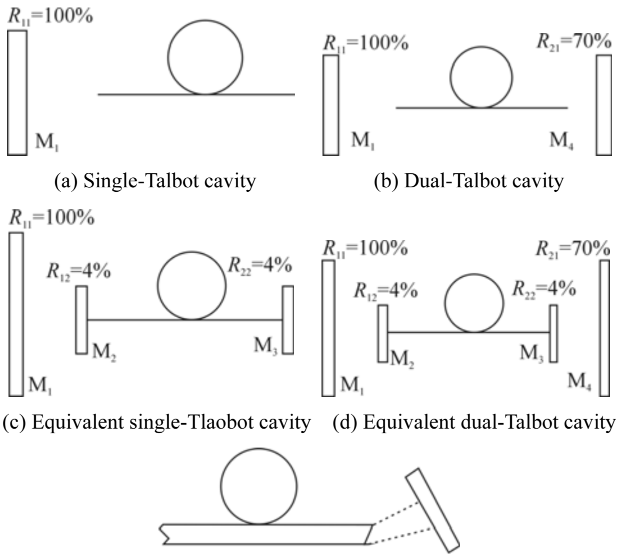
The cores on the end facet of PCF can be regarded as the superposition of several multi-slits in three directions. Accordingly, the distribution of the far-field in-phase mode can be seen as the distribution of five-slit diffraction and interference. By this way, we can figure out how the in-phase mode looks like. There can be a bright central maximum and clear 1st maximum fringe, while the 2nd fringe is ambiguous in five-slit diffration and interference. Correspondingly, the distribution along the symmetry axis in the far-field in-phase mode is just similar to it, but the sizes are not exactly the same because of the different brightnesses and lengths of different silts. But it's suggested that the far-field in-phase mode should have 12 side-lobes besides the center-lobe.

The output of 18-core PCF lasers is the superposition of 18 supermodes. Comparatively, the in-phase mode (n=18) should be locked for its best far-field intensity distribution, that is the central-lobe has not only the high brightness but also the small size.

$\gamma_{m,m}$ is defined as the self-coupling coefficient, and $\gamma_{m,18}$ is defined as the reflection coefficient from in-phase mode to another mode. According to Ref.[12], the decrease of $\gamma^2_{m,m}$ for the 18th mode is slower than those for the 1st–17th modes along with D_1 and D_2 increasing because of its lowest diffraction angle and biggest overlap area between the patterns emitted and reflected, so $\gamma^2_{18,18}$ can dominate after D_1 is greater than 4000 μm in the single-Talbot cavity. Theoretically speaking, the 18th mode can be locked by using single-Talbot cavity. However, we can't capture any satisfactory experimental result in the single-Talbot cavity.

The advantage of dual-Talbot cavity should be explained according to Figs.4 and 5. The single-Talbot cavity is shown in Fig.4(a), which just considers the influence of the left side of PCF. If the contribution of the end facet to the mode selection is included, the single-Talbot cavity should be expressed as Fig.4(c). In Fig.4(c), the Fresnel reflection of the end facet can be equal to a butt-contact mirror of M_2 and M_3 which both have the reflectivity of 4% at 1st–18th modes. But M_2 can be negligible for the existence of M_1 with reflectivity of 100% as a Talbot mirror when we calculate the positive feedback. On the contrary, the effect of M_3 should be taken into account. The positive feedback of each supermode is the product of the reflectivities of supermodes reflected from M_1 and M_3. However, the butt-contact mirror M_3 has no mode selection ability. What's worse, its low reflectivity diminishes the positive feedback of 18 modes.

The dual-Talbot cavity is shown in Fig.4(b). The reflectivity of the M_4 is 70%, and it also acts as an output mirror. Its reflectivity is much greater than that of M_2 or M_3, so M_4 can play a role as a Talbot mirror like M_1. M_4 also has various reflectivities to 18 supermodes. M_1 and M_4 both contribute to the 18th mode to win the mode competition.



(a) Single-Talbot cavity (b) Dual-Talbot cavity

(c) Equivalent single-Tlaobot cavity (d) Equivalent dual-Talbot cavity

(e) Situation with the tilted end facet

Fig.4 Schematic diagrams and the corresponding equivalent schematic diagrams of the single-Talbot cavity and the dual-Talbot cavity

The positive feedback of each supermode considering the self-coupling, which is a product of $\gamma^2_{m,m}$ on left and right end facets of PCF, is shown in Fig.5. Fig.5 shows that the in-phase mode can hold the dominant position considering the self-coupling. According to Refs.[12] and [13], the proportion of the 18th mode is nearly triple the 16th and17th modes when D_1 is 8 mm in single-Talbot cavity. But in the dual-Talbot cavity, the number is increased to approximately 10 times as shown in Fig.5. The leading state of the 18th mode in self-coupling is improved. As to the mutual coupling between the in-phase mode and the other modes, mainly the 11th mode, it has litter effect on output. The 11th mode can receive some energy from the 18th mode after reflecting[12], but it is suppressed by the second Talbot mirror, transmitted to the opposite end facet through the self-coupling. So the 11th mode does not increase much, and it keeps a small proportion.

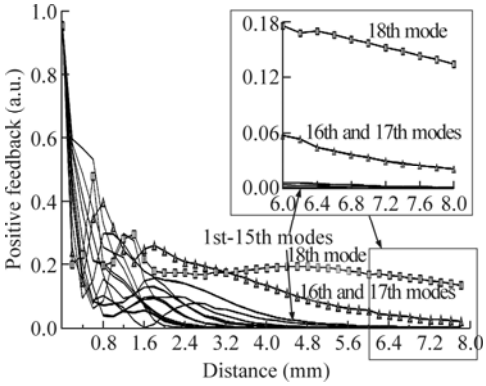
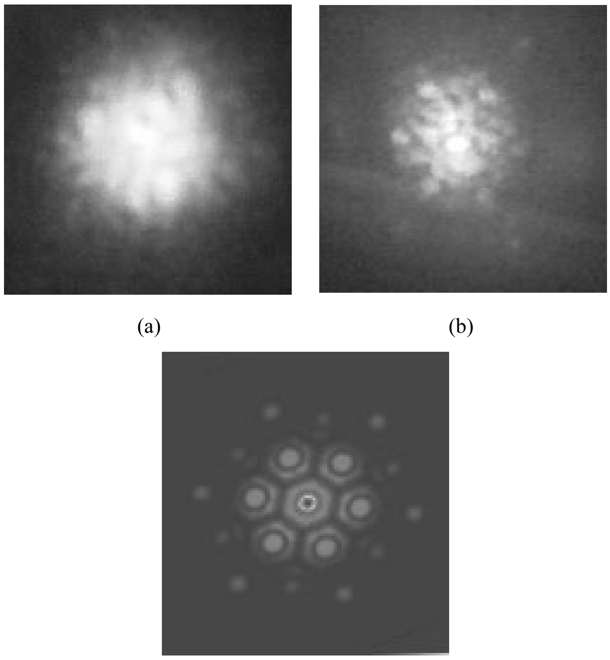


Fig.5 The positive feedback of each supermode at the output end considering the self-coupling where D_1 and D_2 are adjusted together

The end facet of the fiber is processed by cutting and fracturing in this paper to keep the filling factor unchanged. The in-phase mode would be the consequence of interference and diffraction, so it should be multilayer structure but not a simple spot. The filling factor[14,15] should be kept unchanged to compare the far-field calculation results with the experimental results, especially the side-lobes, to judge if the in-phase mode is locked. So it's inevitable to bring some tilted angle to the end facet as shown in Fig.6(e), which transfers the 18th mode to the 1st-17th modes. The added reflect mirror M_4 replaces M_3 on the mode selection, and weakens the adverse effect brought by M_3. What's more, it helps to enhance the in-phase mode. The dual-Talbot cavity helps to hold the dominate position of the in-phase mode.

We conduct the experiment on single-Talbot cavity, but the out-of-phase mode is suppresed a little, and it hardly locks the in-phase mode. The result is shown in Fig.6(a).

The experimental setup is arranged as Fig.1, where D_1 and D_2 are approximately 1 cm, and the electric power of the LD is 17.6 W. Some minor adjustments to the distance and the angle of mirrors are taken carefully to cater for the tilted end facet, which makes the image on the screen clear and stable. The images on the screen of the single-Talbot and dual-Talbot cavities are shown in Fig.6.



(a) (b) (c)

Fig.6 The comparison of the experiment results of the output obtained in (a) the single-Talbot and (b) dual-Talbot cavities; (c) Far-field calculation result of the 18th mode

The distance from the central lobe to the first layer of diffraction lobe is nearly 2 cm when D_3 is approximately 40 cm. Fig.6(b) is an image captured in dual-Talbot cavity. It has some characteristics, such as the bright central lobe and two layers of diffraction lobes with six-fold symmetry compared with Fig.6(c). It is the second layer of diffraction lobes, which confirms the locking of in-phase mode in spite of some ambiguous bright specks between the central lobe and the diffraction lobes.

The output spectrum is measured and shown in Fig.7, and it's a single peak curve.

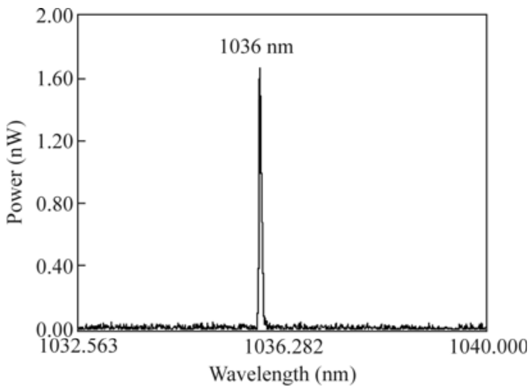


Fig.7 Output spectrum of the multi-core PCF based on dual-Talbot cavity

By adopting the dual-Talbot cavity, we achieve the output in which the in-phase mode is dominant. The dual-Talbot cavity can improve the self-coupling coefficient, the 11th mode from mutual coupling is increased, and it can weaken the adverse effect of end facet of fiber, such as tilt.

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