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Supermode analysis of the 18-core photonic crystal fiber laser

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Abstract The modal of 18-core photonic crystal fiber laser is discussed and calculated. And corresponding far-field distribution of the supermodes is given by Fresnel diffraction integral. For improving beam quality, the mode selection method based on the Talbot effect is introduced. The reflection coefficients are calculated, and the result shows that an in-phase supermode can be locked better at a large propagation distance.

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1 Introduction

Fiber lasers have been an important optical source in many fields of industry and study because of their ability to provide high-efficiency and excellent beam quality even at high-power levels compared with conventional solid laser systems[1~3]. For increasing output power and decreasing nonlinear effects such as stimulated Brillouin or Raman scattering, many novel fiber lasers were proposed[4~6]. Multicore fiber lasers have an advantage of large mode areas (LMAs), resulting in higher power thresholds for nonlinear processes. Because of the distributed nature of the cores, thermomechanical effects are mitigated, unlike in single-core lasers[7]. In recent years, a fiber based on the concept of photonic crystal, the photonic crystal fiber (PCF), has been introduced and attracted considerable interest in many fiber application fields, such as fiber lasers and fiber sensors[8,9]. PCFs can be sorted into two types by a guiding light mechanism— total internal reflection and the photonic band-gap. Various fabrics of PCFs can be designed for special properties according to the number of holes in the PCF and their sizes, shapes, and arrangements. PCFs have greater flexibility compared with conventional fibers. Multicore PCFs combine advantages of the LMA and structure flexibility, and are considered as novel material of fiber lasers. Mafi *et al*. analyzed the modal behaviors of PCFs with two and six cores and compared them with the usual single-core case[10]. Michaille *et al*. reported an experimental result of stable phase locking of six- and seven-core structures through evanescent coupling based on the Talbot effect. And they got a slope efficiency of 70% with up to 44 W of output power[11]. Michaille *et al*. modeled a Q-switched fiber laser with a doped six-core PCF, and a mode filtering technique with a pinhole in the far field was applied[12]. Fang *et al*. realized self-starting mode locking to an 18-core PCF laser by means of a fast semiconductor saturable absorber mirror[13]. In this paper, an 18-core PCF is studied. And 18 near-field patterns of supermodes are presented by using the full-vector finite-element method (FEM). Corresponding far-field patterns of supermodes are also presented by using Fresnel diffraction integral. In the end, supermodes selection by means of Talbot cavity effects is discussed.

2 Structure

The cross profile of the 18-core PCF is illustrated in Fig. 1. Cores in the multicore PCF are arranged in a hexagonal structure, where the cores are Yb-doped silica with a refractive index $n_{co} = 1.445$, the cladding is pure silica with a refractive index $n_{cl} = 1.444$, the air-hole pitch is $\Lambda = 10.1$ μm, the space between the two cores is 2Λ, the diameter of the cores is 16 μm, the diameter of air holes is 4.1 μm, the ratio of the air-hole diameter to the air-hole pitch Λ is 0.406, and the air-filling ratio is 0.15.

3 Supermode distrbution

Each core in the 18-core PCF supports a single mode according to those parameters of the PCF[14]. So the 18-

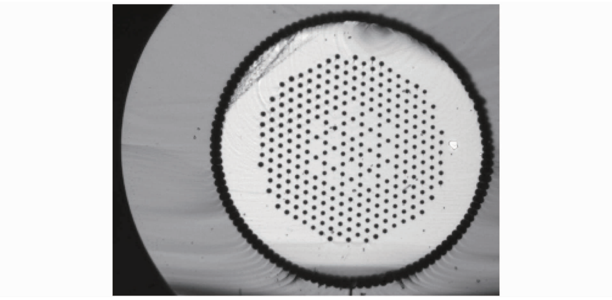

Fig. 1 SEM image of the 18-core PCF.

core PCF laser has the same number of supermodes as its core number. According to coupled mode theory, presumably under weak coupling conditions, the supermodes are approximated as linear superposition of modes of individual cores with appropriate coefficients. In this paper, the FEM is applied to supermode analysis of the 18-core PCF, and the mode field distribution and effective propagation constant can be obtained simply. The electric field intensity distribution of supermodes is shown in Fig. 2. The optical wavelength is 1.064 μm. The supermodes are arranged in increasing order of propagation constant. Fig. 2(a) displays an out-of-phase supermode in which the phase is reverse between arbitrary adjacent cores. The last mode ($n = 18$) is an in-phase supermode in which the phase is equal for every core. The others are mixed supermodes. According to the supermodes of the 18-core PCF simulated by the FEM, electric field distribution across various distances can be obtained by the Fresnel diffraction integral equation[15]:

$$E(x,y)=\frac{\exp(\mathrm{i}kz)}{\mathrm{i}\lambda z}\iint E(x_0,y_0)\exp\left\{\frac{\mathrm{i}k}{2z}\left[(x-x_0)^2+(y-y_0)^2\right]\right\}\mathrm{d}x_0\,\mathrm{d}y_0,\tag{1}$$

whese $E(x_0, y_0)$ is the electric field distribution at the end of the fiber and (x_0, y_0) are the corresponding coordinate positions. Similarly, $E(x, y)$ is the electric field distribution at the observation plane, and (x, y) is the corresponding coordinate position. Z is the distance from the observation plane to the end of the fiber. Fig. 3 shows the far-field ($Z = 10,000$ μm) intensity distributions of several supermodes. In Fig. 3, the in-phase supermode ($n = 18$) provides the best beam quality with a near Gaussian far field whereas the out-of-phase supermode ($n = 1$) has the largest diffraction angle in the far field.

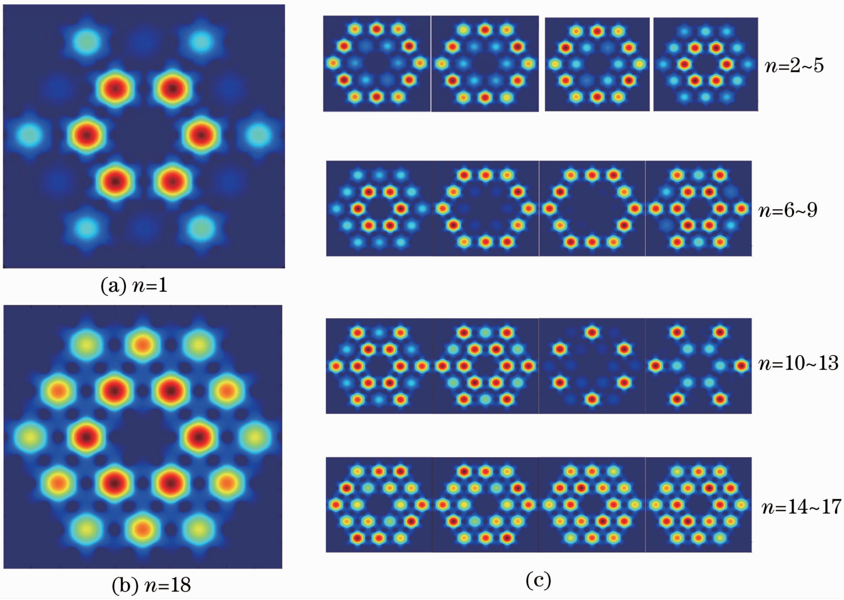

Fig. 2 Electric field intensity distributions of supermodes in the 18-core PCF. (a) Out-of-phase supermode; (b) in-phase supermode; (c) mixed supermodes.

4 Supermode selection

Fig. 3 shows that an in-phase supermode has a better far-field intensity distribution than other supermodes. The intensity distribution of the output beam of multicore PCF lasers is a mix supermode. For improving the beam quality while maintaining high output power, it is necessary to lock the in-phase supermode in the multicore PCF laser while suppressing the out-of-phase supermode. The Talbot effect can be observed in a periodic laser array. Based on that effect, phase locking can be simply established[16]. When a plane wave is transmitted through a grating or another

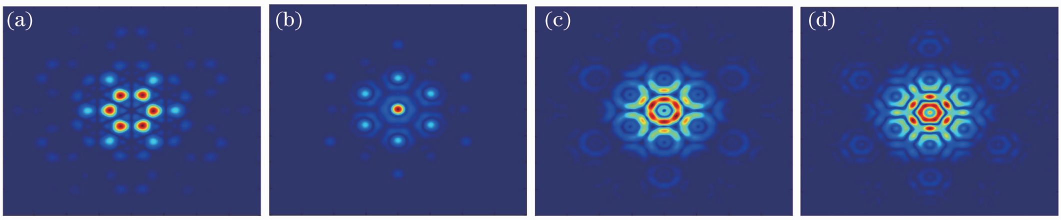

Fig. 3 Far-field ($z = 1$ cm) intensity distributions of supermodes. Far-field intensity distributions of an (a) out-of-phase and (b) in-phases supermode; far-field intensity distributions of the supermodes in which the (c) first and (d) second rings are out of phase.

periodic structure, the resulting wave front propagates in such a way that it replicates the structure at multiples of a certain defined distance, known as the Talbot length. The Talbot length is given by

$$Z_{\mathrm{T}} = m\frac{2d^2}{\lambda}, \tag{2}$$

where d is the period of intensity distribution of the supermode, λ is the optical wavelength, and m is a positive integer. In Fig. 2, different supermodes have different Talbot lengths. A mirror is placed properly at half the Talbot length of the wanted supermode to establish the Talbot cavity. The different supermodes have different diffraction angles. The in-phase supermode has the minimum angle, while the out-of-phase supermode has the maximum angle. Because the size of the end of the PCF is finite, only supermodes with small diffraction angles can enter the 18-core PCF and be locked. The Talbot cavity images the wanted supermode back into the 18-core PCF so that the particular supermode would be amplified more efficiently, achieving a dynamical phase locking.

For evaluating the effect of each Talbot length, the amplitude reflection coefficient γ is given by[16,17]

$$\gamma_{m,n}(z) = \frac{\left|\iint_{\infty} E_m^*(z=0)E_n(z)\,\mathrm{d}x\mathrm{d}y\right|}{\iint_{\infty} |E_m(z=0)|^2\,\mathrm{d}x\mathrm{d}y}. \tag{3}$$

The function is defined by the normalized correlation integral of the emitted field of the wanted supermode and the corresponding wave reflected from the mirror; it depends on the emitted field distribution and on the propagation distance z, which equals twice the mirror distance z_m. $E_m(z=0)$ denotes the field distribution of the wanted supermode, and $E_m(z=2z_m)$ represents the reflected wave field of the corresponding supermode. The calculated amplitude reflection coefficients of all supermodes to the 18-core PCF are shown in Fig. 4. Fig. 4(a) is the self-coupling reflection coefficient $\gamma_{n,n}$. The supermodes of $n = 3(4)$, $n = 5(6)$, $n = 7(8)$, $n = 9(10)$, $n = 14(15)$, and $n = 16(17)$ produce identical reflection coefficients, and the in-phase supermode ($n = 18$) has the largest reflection coefficient for large values of z. The in-phase supermode is completely distinguished from the other supermodes, and one can achieve phase locking by placing a mirror at a suitable large distance. According to Fig. 4(a) and 3(b), we can predict that the output of

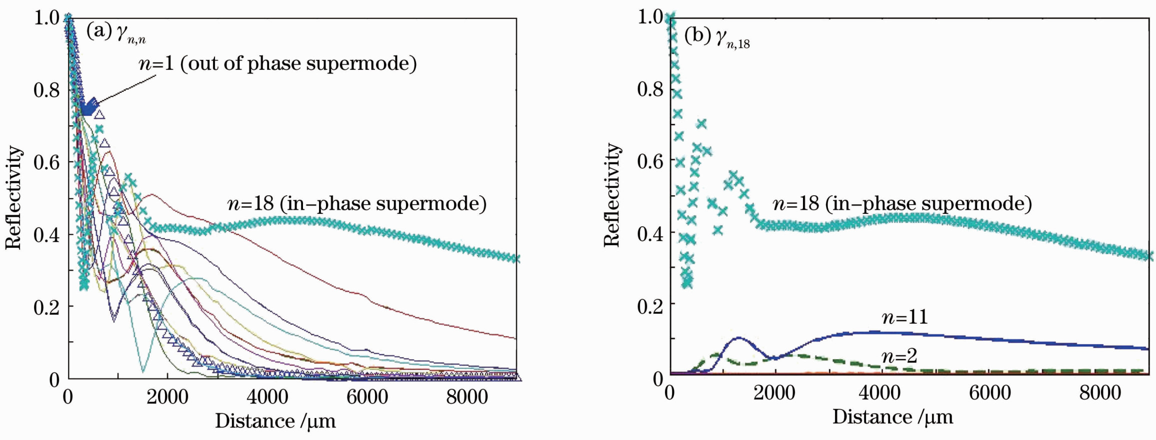

Fig. 4 Theoretical reflection coefficient for each supermode of the 18-core fiber using a mirror. Triangles are the reflection coefficients of the out-of phase supermode, and that of the in-phase supermode shown by crosses and that of the out-of-phase supermodes shown by solid line are the other reflection coefficients from other supermodes. (a) Self-coupling reflection coefficient; (b) reflection coefficient from the in-phase supermode to all supermodes.

the 18-core PCF laser is an approximate Gaussian beam and that the majority is the in-phase supermode. Fig. 4(b) is the reflection coefficient from the in-phase supermode to all supermodes $\gamma_{n,18}$, which is negligible except for the supermodes of $n = 11$ and $n = 2$. From Fig. 4(b), we can also find that the in-phase supermode is orthogonal with other supermodes except for the second and eleventh supermodes.

5 Conclusion

The multicore PCF laser attracts more and more attention for producing a high-power and good beam quality. The 18-core active PCF is studied for its LMA. Near-field intensity distributions of the supermodes are numerically calculated based on the FEM, and the corresponding supermode distribution patterns are drawn. Based on Fresnel diffraction integral, far-field intensity distributions of the supermodes are given. For making the multicore fiber laser preferentially operate in a particular supermode, improving the beam quality, the phase-locking method based on the Talbot external cavity is introduced. The amplitude reflection coefficients of different supermodes are given and show that an in-phase supermode has the largest reflection coefficient for large values of z.

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