Investigation of modal properties of microstructured optical fibers with large depressed-index cores

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We present what is, to the best of our knowledge, the first systematic study on how negative core–cladding index difference influences microstructured optical fiber's modal behavior. Single-mode lasing has been realized for short-length cladding-pumped phosphate glass microstructured fibers with large depressed-index $Er^{3+}-Yb^{3+}$-codoped cores. © 2005 Optical Society of America

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Microstructured optical fibers (MOFs), with high-index solid cores surrounded by patterned claddings,[1] are attractive for interesting applications such as high-power fiber lasers. The cores of MOFs are formed by filling (missing) one or multiple air holes in the otherwise periodic air hole structure. Endless single-mode (SM) core guidance has been observed in MOFs whose cores are formed by filling one air hole,[2] while SM operations have been realized on MOFs with extended core areas, e.g., cores formed by filling three[3] or seven[4] air holes. The seven-missing-hole MOF (MOF7) effectively provides large-mode-area (LMA) SM guidance that usually cannot be achieved by step-index fibers (SIFs); at the same time, only a small number of air hole shells are necessary to confine the modes. Our simulation shows that otherwise identical MOF7s with 3, 4, and 5 rings of holes have almost identical fundamental mode distributions, as shown in Figs. 1(a)–1(c), respectively. The outer diameter (OD) of the LMA MOF7 can thus be kept compatible with commercial fibers (125 μm OD); in comparison, to obtain a similar core area and modal confinement, a one-missing-hole MOF (MOF1) needs to expand its OD almost three times, as shown in Fig. 1(d). This requirement results in increased material cost and physical incompatibility with commercial fibers; e.g., the mismatch of fiber sizes increases loss for fusion splicing.

A default assumption for fabrication and analysis of SM MOF is zero index difference ($\Delta n = n_{\mathrm{core}} - n_{\mathrm{clad}}$) between the core material index (n_{core}) and the cladding material index (n_{clad}), which is naturally satisfied by passive MOFs made entirely from the same material. However, for active MOFs with doped cores, this condition requires attention. The addition of active ions inevitably changes n_{core}, and other dopants can, in principle, be added to tailor both n_{core} and n_{clad}. Although this index tailoring poses a fabrication challenge, it also adds flexibility to the fiber design. While several Yb^{3+}-doped silica LMA MOFs have been reported under SM operation with slightly positive Δn,[4,5] there is a lack of systematic study on how Δn influences the MOF's modal property. In particular, there is no study of the interesting case where Δn is negative (core index is depressed, $n_{\mathrm{core}} < n_{\mathrm{clad}}$). Such a condition results in antiguiding for SIFs, but we will demonstrate that stable guidance and SM lasing are possible for MOFs owing to the existence of the air holes, which effectively suppresses n_{clad}.

In this Letter we report, to the best of our knowledge, the first systematic study on how negative core–cladding Δn affects the modal property of MOF. We have fabricated MOFs with various Δn and structural parameters and studied their modal behavior. SM operation has been achieved for MOFs with the proper choice of Δn and structure. We have also calculated beam qualities of guiding modes of different orders and extended the effective V parameter (V_{eff}) calculation[2] to MOF7. Simulations and measurements agree very well. Our study has focused on phosphate MOFs with $Er^{3+}-Yb^{3+}$-codoped cores; however, the results can be applied to fibers of any host glass. We demonstrate that, by depressing the core index, the technical difficulty in pursuing extremely small Δn for LMA MOFs can be waived, resulting in relaxed tolerance and more flexibility in fiber design and fabrication.

Active MOFs have been extensively utilized for fiber amplifiers and lasers, e.g., Yb^{3+}-doped silica MOF[4,5] at ~1.1 μm and $Er^{3+}-Yb^{3+}$-codoped phosphate MOF[6] at ~1.5 μm. A Yb^{3+}-doped MOF7 with a SM core area of $\sim 10^3$ μm^2 has been reported,[4] with a small positive Δn ($\sim 10^{-5}$). However, with such a superior index control technique, there does not seem to

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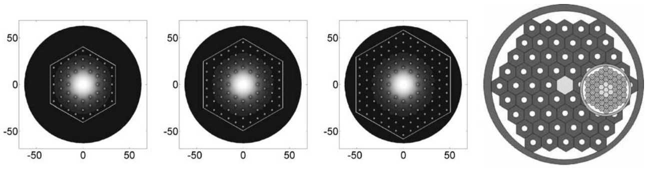

(a) (b) (c) (d)

Fig. 1. Calculated fundamental mode distributions for MOF7s: $\Delta n = -7 \times 10^{-4}$, $d_{\mathrm{AH}}/\Lambda = 0.15$, with (a) three, (b) four, and (c) five rings of holes. All three MOF7s have the same (~70%) confinement for the fundamental mode. (d) Comparison between a MOF7 and a MOF1 with the same core area demonstrates that the MOF1 demands a much larger physical size.

be an advantage of using a MOF design: a SIF with the same Δn can have a SM core area as large as $\sim 1.5 \times 10^4\ \mu\mathrm{m}^2$. In order to take full advantage of MOF's unique modal properties[1–3] and relax the tight tolerance in index control, we have studied the alternative approach of introducing a negative Δn. The core index is depressed so that the MOF core will be leaky until the holes in the cladding open up to a certain size, and the modal quality can be controlled by properly choosing Δn and air hole size. In this Letter we investigate the effect of negative Δn as well as air hole diameter (d_{AH}) on the modal behavior of MOF7, both experimentally and theoretically.

The MOFs under study are made of phosphate glasses, and they have been used to fabricate short-length MOF lasers.[6] Our MOFs all have a 125 μm OD, a 9 μm pitch Λ (air hole pattern periodicity), an active core area of $\sim 430\ \mu\mathrm{m}^2$, but have various d_{AH}. It has been well known that the MOF modal properties are decided by two relative ratios,[3] Λ/λ and d_{AH}/Λ. In our case Λ/λ is fixed ($= \sim 6$ at $\lambda = 1.5\ \mu$m), and we investigate the effect of d_{AH}/Λ only. MOFs were drawn with various d_{AH}, starting with no holes ($d_{\mathrm{AH}} = 0$) to maximal holes ($d_{\mathrm{AH}} = \sim 0.5\Lambda$). Our MOF cores were doped with 1 wt. % Er_2O_3 and 2 wt. % Yb_2O_3. Other codopants were added to selectively tailor the negative Δn. Three Δn values were introduced: -15×10^{-4}, -7×10^{-4}, and $-5 \times 10^{-4} < \Delta n < 0$, respectively. The indices were measured with a prism coupler, and the uncertainty in the last Δn value was due to the instrument resolution.

Short-fiber lasers operating at 1.5 μm were made from MOF7, which were ~11 cm long with both ends cleaved. One advantage of utilizing such short MOFs is that the fiber bend loss is no longer a concern. Bend loss has to be considered when long fiber is coiled for SM operation; however, our MOF is designed for short-length applications, and SM operation is achieved by tailoring the fiber design. Our MOF is always used in the straight form, and the bend loss can thus be ignored. The short fiber lasers were end pumped with 975 nm pump light launched into the MOF cladding by a multimode fiber, whose facet was coated with dielectric layers. The pump fiber was butt coupled to one end of the MOF, and the coating served as the high reflector (at 1.5 μm) of the laser cavity. A beam profiler was used to measure the M^2 value of the output beam exiting the other MOF end. The M^2 values, all taken under ~3.5 W pump power, are plotted versus d_{AH}/Λ in Fig. 2. MOF7s with three Δn values are compared in Fig. 2.

In the figure we notice that all three M^2 curves have similar shapes: they start with relatively large M^2 values at small holes, followed by a sharp drop to a minimum, then increase again, gradually. The antiguiding behavior with small holes confirms that all our MOFs have depressed-index cores. SM laser operation begins when d_{AH}/Λ reaches a threshold, and it is a sudden transition from antiguiding to SM guiding, as shown by the steep M^2 drops. The threshold is decided by Δn: the larger $|\Delta n|$, the higher the threshold. Thus the leftmost curve represents MOFs with a minimal Δn, and the rightmost has the largest Δn (-15×10^{-4}). Fundamental mode operation was confirmed by observation of the far-field pattern, though we notice that the best M^2 value measured is 1.7, not diffraction limited. The higher M^2 value has two reasons: first, the MOF's fundamental mode shape deviates from a Gaussian mode[1,6]; second, the MOF has high internal stress originating from its stack-and-draw fabrication process, which may deteriorate the modal quality. A fine annealing process was performed on the MOF7 with $\Delta n = -7 \times 10^{-4}$ to release the stress, and we found that the tested modal quality did improve, as the best M^2 value dropped to <1.5 (inset of Fig. 2). The annealing also might have changed Δn, as the annealed M^2 curve is seemingly shifted to the right and the annealed fibers become leaky with small holes. Details of the annealing effects are being studied and will be reported elsewhere. Passing the SM regime, high-order modes sequentially appear as d_{AH}/Λ increases, and the beam quality deteriorates gradually with increasing M^2 values.

To explain the experimental results, a finite-element method model has been developed to calculate the MOF's modal behavior.[7] As an example, the calculated modal qualities (M^2 values) of a MOF7

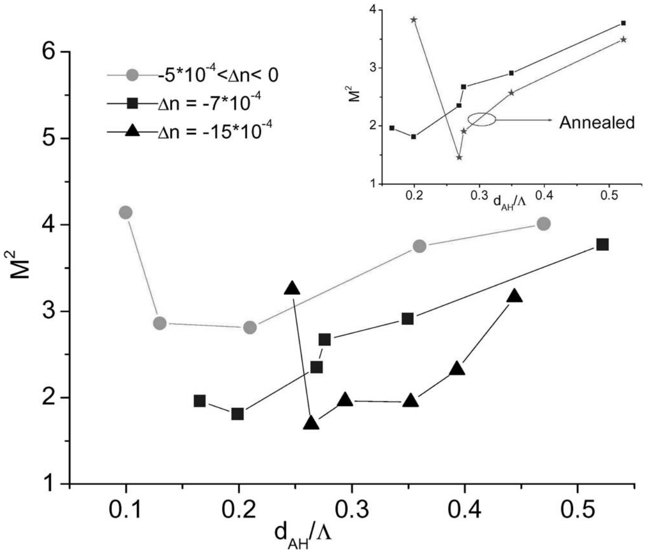

Fig. 2. Measured M^2 values versus d_{AH}/Λ of MOF7s with three Δn values. Inset, effect of annealing on MOF7s initially having $\Delta n = -7 \times 10^{-4}$.

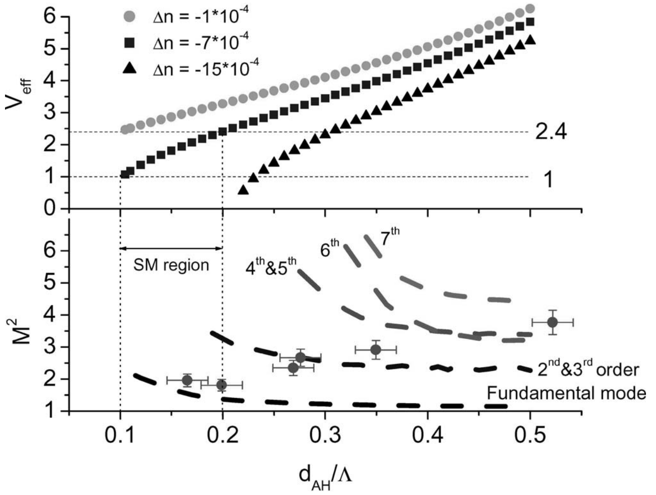

Fig. 3. Upper, calculated V_{eff} of MOF7s with three Δn values; lower, simulated (curves) and measured (dots) beam qualities for MOF7s with $\Delta n = -7 \times 10^{-4}$.

with $\Delta n = -7 \times 10^{-4}$ are plotted in lower Fig. 3, along with the measured values. The simulation shows that while the fundamental mode always provides high-quality beams with $M^2 < 2$, the modal quality rapidly deteriorates for high-order modes—it is thus important to find the modal cutoff of MOF7. As introduced by Birks *et al.*,[2] V_{eff} can be defined for MOF, equivalent to the V parameter for SIF:

$$V_{\mathrm{eff}} = \frac{2\pi R}{\lambda} \sqrt{{n_{\mathrm{core}}}^2 - {n_{\mathrm{FSM}}}^2}, \tag{1}$$

where n_{FSM} is the effective index of the fundamental space-filling mode and R is the core radius that has been defined differently for MOF1 in the literature.[2,8,9] However, R has never been defined for MOF7; therefore, we extend the V_{eff} concept by selecting R as the radius of the circle that has the same area formed by the seven hexagonal core cells, which is the most natural choice. The calculated V_{eff} for MOF7s with three Δn values, closely matched to our fabricated fibers, are plotted in upper Fig. 3. Using the criteria for SIF, $V_{\mathrm{eff}} = 2.4$ is the SM cutoff, and the core is considered leaky below $V_{\mathrm{eff}} = 1$, where the fundamental mode confinement is $<20\%$. Thus, for MOF7 with $\Delta n = -7 \times 10^{-4}$, the SM range is $V_{\mathrm{eff}} = [1, 2.4]$, corresponding to $d_{\mathrm{AH}}/\Lambda = [0.1, 0.2]$. As is seen from lower Fig. 3, the modeling agrees well with the experimental data.

Figure 3 also shows that MOFs with different Δn have similar modal behaviors, but at different d_{AH}/Λ regimes. When Δn is small (-1×10^{-4}), the SM regime is within the small-holes region ($d_{\mathrm{AH}}/\Lambda < 0.1$). In addition, the beam is generally not of the best quality (Fig. 2). As Δn becomes larger (-7×10^{-4}), the SM regime becomes broader, and the modal quality also improves. A further increase of Δn (-15×10^{-4}) again reduces the SM regime. Thus we can conclude that there exists an optimal Δn, about -7×10^{-4} in our case, that has a reasonable SM range and is relatively easy to manufacture with large tolerance. The core-index-depressed MOF7 can provide SM operation but only within a certain d_{AH}/Λ range that is determined by Δn. This is in sharp contrast to the endless SM property of MOF1.[2] The reduced SM regime of the MOF7s is not a surprise, since this tendency has been seen from the three-missing-hole MOFs.[3] For some applications, this might offset the benefit in mode area enhancement, while for applications such as short-length high-power fiber lasers the gain in active core area in a MOF7 should clearly compensate for the limits in design parameters.

In summary, the modal property of phosphate LMA MOF7 with a depressed-index active core has been experimentally and theoretically investigated. SM guiding has been demonstrated from short MOF7 with an appropriate index profile and structure. Thus, we have demonstrated practical ways to tailor the MOF modal property while providing flexibility in fiber design and relaxing conditions for index control.

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