Short-length microstructured phosphate glass fiber lasers with large mode areas

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We report fabrication and testing of the first phosphate glass microstructured fiber lasers with large Er–Yb-codoped cores. For an 11-cm-long cladding-pumped fiber laser, more than 3 W of continuous wave output power is demonstrated, and near single-mode beam quality is obtained for an active core area larger than 400 μm^2. © 2005 Optical Society of America

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One of the most interesting properties of the recently developed microstructured optical fibers[1,2] (MOFs), also known as photonic crystal or holey fibers, is their endless single-mode (SM) behavior.[3–6] These MOFs have air holes that are arranged in a two-dimensional triangular pattern and run through the whole fiber length. Typically, one hole in the center of the periodic structure is intentionally ignored, which forms a solid core area surrounded by the patterned cladding. The optical characteristics of these MOFs are influenced by two relative length scales: d/Λ, where d is the hole diameter and Λ is the pitch (the center-to-center spacing of neighboring holes); and Λ/λ, with λ being the wavelength. It has been shown that MOFs provide SM guiding if the d/Λ ratio is below a certain limit[5,6] (~ 0.45), regardless of the Λ/λ value. This fiber design thus provides a natural solution to one critical problem faced by high-power short-length fiber lasers: how to achieve SM operation with a sufficiently large mode area (LMA).[7,8]

Short LMA fiber lasers, with active fibers as short as only a few centimeters, besides having the obvious advantage of making very compact devices possible, also suppress nonlinear effects to allow for power scaling and provide the possibility of single-frequency operation when assisted by narrow-linewidth elements such as fiber Bragg gratings.[9] For a conventional SM step-index fiber, however, owing to the achievable precision in refractive-index control, it is extremely difficult to expand the core area beyond 400 μm^2 without additional mode-filtering techniques. On the other hand, for an endless SM MOF, the whole fiber cross section can be scaled up while preserving the modal property. In addition, MOFs provide large flexibility in fiber design, e.g., the core area can be further increased by leaving out multiple holes in the center.[6,10,11]

In this Letter we present what is to the best of our knowledge the first MOF fabricated of phosphate glass (PG). Though MOFs are most commonly made of silica, nonsilica fibers have been investigated recently for their unique properties such as high nonlinearity and high refractive index.[12,13] PG is of particular interest owing to its high solubility of Er and Yb ions[14] as well as its large phonon energy to assist Er^{3+} $^4I_{11/2}$ to $^4I_{13/2}$ relaxation,[15] which makes it a superior host glass for amplifier and laser applications at ~ 1.5 μm. A high-power SM PG fiber laser with a step-index core area of 150 μm^2 has been reported by our lab[8]; by applying the MOF approach to PG fiber, we gain the potential to boost the output power by expanding the core area considerably while preserving the beam quality. To study the effect of fiber design parameters on beam quality, we have drawn and tested fibers with either one or seven central holes missing, with the doped core glass having a slightly lower refractive index than the cladding glass. Based on these PG MOFs, we fabricated cladding-pumped fiber lasers only a few centimeters in length. Though other MOF lasers have been realized recently,[10,16,17] all of them used several meters of Yb^{3+}-doped silica fibers. Our short PG MOF laser delivered more than 3 W of continuous wave (cw) output power, and the dependence of the output beam quality on the fiber geometry and the d/Λ ratio was systematically studied.

We used P_2O_5 as the glass former, and the PGs were made by NP Photonics, Inc. The fibers were drawn at the Optical Sciences Center by the stack-and-draw technique. Two different PG preforms were made; one was undoped with a hole drilled in the center, and the other was Er–Yb codoped without a hole. Both preforms were drawn to stacking cells, which were stacked together with the core cell(s) placed in the center, and the whole stack was inserted into a tube made of another undoped PG. The tube glass had a lower index to confine the pump light inside the patterned cladding. The stacked tube was drawn to obtain the MOF. Figure 1(a) illustrates the stacked tube and Fig. 1(b) shows the drawn MOF with seven

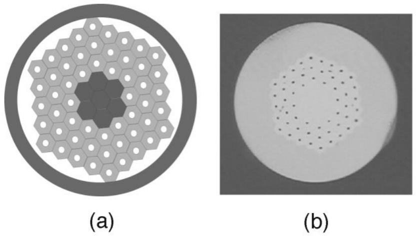

Fig. 1. (a) Illustration of the stacking scheme. (b) Microscopic image of MOF7 with an OD of 125 μm.

core cells. By adjusting the drawing temperature, MOFs were fabricated with an identical outer diameter (OD) and pitch Λ but different d/Λ ratios.

The MOF cores were doped at levels of 1.1×10^{26} Er^{3+} ions/m^3 and 2.2×10^{26} Yb^{3+} ions/m^3. Doping the core inevitably introduced an index difference ($\Delta n = n_{\mathrm{core}} - n_{\mathrm{clad}}$). Considering that (i) a positive core–cladding Δn would bring the MOF back to the step-index fiber limitation and that (ii) the accuracy of our index measurement was limited to $\pm 5 \times 10^{-4}$, we chose the core and cladding glasses with $\Delta n = -7 \times 10^{-4}$, nominally. We verified experimentally that our MOFs had depressed-index cores because the cores showed an antiguiding property until the holes opened to a certain size.

In the fiber laser experiments we constructed lasers by using 11-cm-long MOFs with both ends cleaved. The fiber lasers were cooled by a thermoelectric cooler to remove the generated heat. Up to 31 W of 975-nm pump light was delivered through a multimode fiber (core diameter of 105 μm) whose output facet was coated. The coating was transparent at 975 nm and highly reflective at 1.5 μm. The coated pump fiber end was butt coupled against the MOF so that the pump light was effectively injected into the MOF cladding, and the coating served as a high reflector for the laser cavity. The Fresnel reflection at the other end of the MOF served as the output coupler. The output beam was monitored by a real-time beam profiler for the M^2 value measurement.

Six different MOFs of one hole missing (MOF1) were drawn with d/Λ varying from 0.14 to 0.46, and their OD and Λ were kept at 125 and 9 μm, respectively. We obtained SM outputs from all six MOF1 lasers as expected from the design parameters.[3–6] However, since the fundamental mode of MOF1 differed considerably from a circularly symmetric Gaussian mode,[1] both our modeling and experiment showed that its M^2 value could be considerably larger than 1, the value of an ideal Gaussian beam. The M^2 value increased with the reduced d/Λ ratio (Fig. 2), because of the less modal confinement caused by smaller holes, and the modeling agreed well with the measured data. The output powers of MOF1 lasers were fairly low because of the small core areas of ~ 60 μm^2.

The power performance was boosted for MOFs with seven holes missing (MOF7) owing to the large increase in active core area. With the same OD and Λ as MOF1, MOF7 had a core area of ~ 430 μm^2. Our 11-cm-long MOF7 laser was able to generate 3.1 W of cw optical power at 1.53 μm, with 31 W of 975-nm pump light launched. Figure 3 shows the signal versus pump plot for two MOF7 lasers with d/Λ of 0.50 and 0.19. Both fiber lasers produced almost identical output power characteristics. The output spectrum was centered at 1535 nm with a width of ~ 4 nm. The lasing threshold was <3 W, and the slope efficiency was $\sim 11\%$ against the launched pump power. The pump absorption coefficient and propagation loss coefficient were measured to be 0.20 and 0.05 cm^{-1}, and the output-end pump leakage was $<5\%$. Thus there is only a negligible benefit of working with a longer MOF7. Note, however, that we started with relatively low doping levels to focus on the MOF design and fabrication. The output power and slope efficiency can be dramatically increased if the cores are doped as high as in Ref. 8 and the propagation loss is reduced by an improved fiber drawing process. We expect ~ 10 W of fiber laser output from a 5-cm-long MOF laser with optimized doping and fabrication.

For MOF7 lasers the measured M^2 value decreased steadily when d/Λ shrank (Fig. 4), which was in striking contrast to the behavior of MOF1 (Fig. 2). At the smallest $d/\Lambda = 0.19$, we observed $M^2 < 1.5$. To interpret our experimental results, we calculated the M^2 value of the fundamental mode as well as those of the degenerated second- and third-order modes that could propagate in MOF7, shown as the dashed curves in Fig. 4. A comparison of the modeling and experimental data indicated that MOF7 with larger d/Λ supported several modes, whereas SM behavior could be approached for $d \leqslant 0.2\Lambda$. This presumption

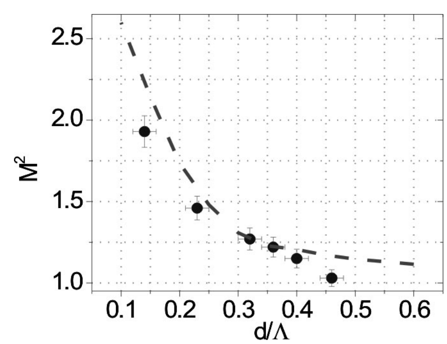

Fig. 2. M^2 value versus d/Λ ratio for MOF1 lasers. The dots are data measured at 10 W of pump power. The dashed curve shows the calculated M^2 value of the fundamental mode, assuming $\Delta n = -7 \times 10^{-4}$ and $\Lambda/\lambda = 6$.

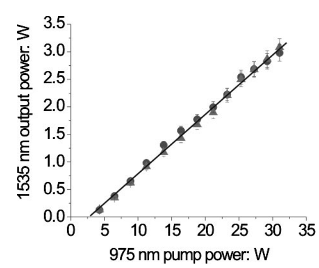

Fig. 3. Signal output versus pump power of two MOF7 lasers. The dots correspond to a MOF7 of $d/\Lambda = 0.19$ and the triangles represent a MOF7 of $d/\Lambda = 0.50$.

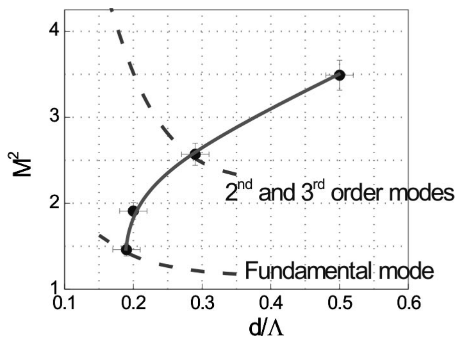

Fig. 4. M^2 value versus d/Λ ratio for MOF7 lasers. Dots, experimental; the solid curve is for visual assistance only. Dashed curves, calculated M^2 values for the fundamental mode and second- and third-order modes.

was supported by the observed far-field pattern, which had a bright central spot surrounded by six much dimmer spots seated at the hexagon vertices. This pattern is similar to that of the previously reported one-hole-missing MOF,[1] and thus provides indication of fundamental mode operation of the MOF7. Note that the improved beam quality for the MOF7 laser with smaller d/Λ did not result in any penalty with respect to output power, as demonstrated in Fig. 3. The plotted M^2 values were measured with a 4-W pump, and we observed a moderate increase at high-power operation; e.g., for MOF7 with $d/\Lambda=0.19$, the M^2 increased to almost 2.0 at the highest pump level. Our results clearly indicate that SM behavior and good beam quality can be preserved in the LMA MOF7, even though its core area is seven times as large as that of MOF1. We expect to improve the beam quality further by fine adjustment of d/Λ and Δn. A study of the effect of Δn and internal stress on the beam quality is in progress.

In summary, we have demonstrated short-length cladding-pumped MOF lasers made of phosphate glass. Single-mode operation has been demonstrated, and more than 3 W of cw output power has been obtained from an 11-cm-long active MOF with a core area of 430 μm^2. We expect that fine adjustment of the MOF design, further expansion of the core region, and an increase of the doping level will result in a drastic increase of the output power while maintaining single-mode, near-diffraction-limited beam quality.

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