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Yb-doped large mode area fibers with depressed clad and dopant confinement

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ABSTRACT

Large mode area fibers with depressed-index cladding layer and confinement of rare-earth dopants can provide effective suppression of high-order modes. A polarization-maintaining Yb-doped double-clad fiber with 35/250 μm core/clad diameter has been fabricated from conventional methods according to this design. The fiber which has an effective mode area close to 500 μm^2 yields near diffraction-limited output with beam quality factor M^2 close to 1.1 when tested as a power amplifier with a coherent seed light source. Beam pointing measurements provide further evidence for near single-mode behavior as the pointing fluctuations are shown to be negligible once the fiber is coiled to a given diameter.

Keywords: Fiber amplifier, Large mode area, Ytterbium, Depressed-clad, Dopant confinement, Beam quality

1. INTRODUCTION

Large mode area (LMA) optical fibers were instrumental to the development of high power fiber lasers and amplifiers in the past fifteen years as MW peak power and mJ energy are now readily achieved before the onset of nonlinear effects because of much reduced intensities[1-2]. As the core of conventional LMA fibers gets larger and the numerical aperture smaller, preserving near single-mode guidance becomes challenging as the waveguide is supporting an increasing number of modes and the effective-index space collapses, making intermodal coupling between fundamental and higher-order modes (HOMs) difficult to avoid[3-4]. Besides, differential bending loss between fundamental mode and HOMs vanishes as the propagation constants get closer, making mode discrimination by coiling the fiber less practical. Ultimately, poor beam quality and beam pointing stability are to be expected as a result of coherent superposition of different transverse modes[5].

Several strategies have been reported in the literature in the last decade or so to enforce effective single-mode behaviour of LMA fibers[6]. This can be achieved either through preferential amplification of the fundamental mode or otherwise by imparting higher propagation losses to HOMs. Selective doping and multi-layer claddings with depressed index inner layer are two such schemes. The former promotes preferential amplification of the fundamental mode through confinement of rare-earth dopants to the central portion of the core providing higher overlap of the gain with the fundamental mode[7] (also known as gain filtering) whereas the latter results in increased differential bending losses as a result of the lower effective numerical aperture seen by HOMs[8] when the fiber is coiled according to reasonable bend radii. Both of these methods are shown herein to be quite effective at suppressing HOMs for fibers with large core diameters when implemented together.

A polarization-maintaining Yb-doped double-clad fiber with 35/250 μm core/clad diameter has been fabricated from modified chemical vapor deposition (MCVD) process in conjunction with rod-in-tube sleeving technique according to this design. The fiber which has an effective mode area close to 500 μm^2 yields near diffraction-limited output with beam quality factor M^2 close to 1.1 when tested as a power amplifier with a coherent seed light source. The exceptional beam quality is maintained for high power, well over 20dB of gain. Beam pointing measurements provide further evidence for near single-mode behavior as the pointing fluctuations are shown to be negligible. Besides, the beam characteristics are further examined for coupling conditions that yield a significant fraction of energy into HOMs in order to show how effective is the suppression of these modes. In the following, the LMA fiber design is first described in light of proper theoretical considerations. Then, experimental evidences for the effective single-mode behavior of the waveguide are reported. Finally, brief concluding remarks along with future directions are outlined.

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2. LMA FIBER DESIGN

A polarization-maintaining LMA fiber featuring a depressed-index cladding layer and confinement of ytterbium dopants has been designed and drawn (see Fig. 1). The fiber core preform was fabricated through conventional MCVD method and solution doping whereas the complete preform was assembled following rod-in-tube sleeving. The core chemical composition is based on phosphorus/aluminum co-doped silica glass. Dopants concentration ratio (P_2O_5/Al_2O_3) was adjusted such as to minimize photodarkening loss[9]. The fiber core has a diameter of 35 µm and NA of 0.06 whereas the pump guide has a diameter of 250 µm and NA of 0.50. The confinement factor of Yb dopant in the core (about 2/3) is near optimal[8], i.e. the differential gain as a result of mode overlap with rare-earth dopants is maximized. Absorption of the fiber at 915 nm pump wavelength is slightly below 1.0 dB/m. The refractive index profile features a small depression at the inner portion of the 1st cladding layer. Once the fiber is coiled, evanescent field of HOMs extends further beyond the depressed index cladding layer, thus lowering the effective numerical aperture of HOMs because of the greater overlap with outer cladding layer. The latter makes discrimination of HOMs more efficient as there is fewer of them and they are more easily suppressed. In effect, the depressed clad layer thickness and index difference were chosen such as to maximize the differential bending loss between fundamental mode and HOMs. The enhanced bend-induced loss attributable to the depressed-index cladding layer is not based on resonant coupling of HOMs to cladding structure and is thus eminently more simple to produce as concerns fabrication tolerances than other designs advocated in the literature. The fiber birefringence was measured to be as high as $2.0 \cdot 10^{-4}$ which is expected to yield good polarization extinction.

The refractive index profile of the fiber shown in Figure 1 has been measured using refracted near-field technique (Photon Kinetics S14 profiler). Numerically solving Maxwell's equation for the waveguide through finite-difference analysis using index profile data yields quasi-Gaussian LP_{01} intensity distribution with effective mode area (A_{eff}) close to 500 μm^2 (see Fig. 2) and beam propagation factor $M^2 = 1.02$. Besides from the LP_{01} mode, the twofold degenerate LP_{11}

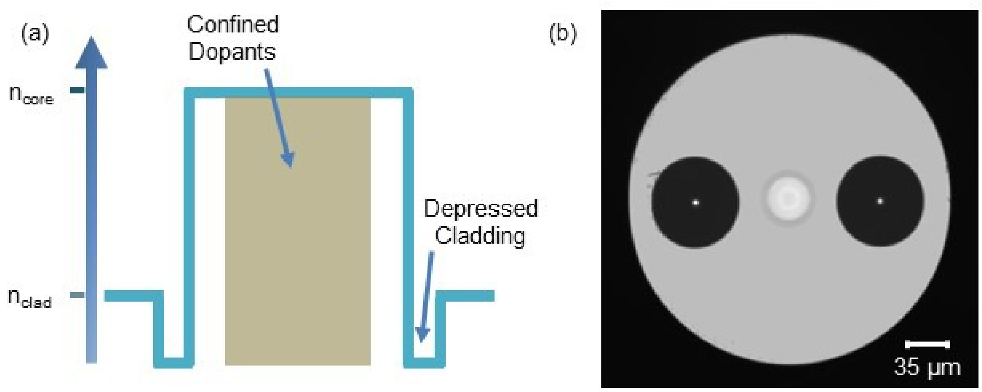


Figure 1. Schematic representation of the LMA fiber refractive index profile (a) along with an optical micrograph (end-view) of the fabricated LMA fiber (b).

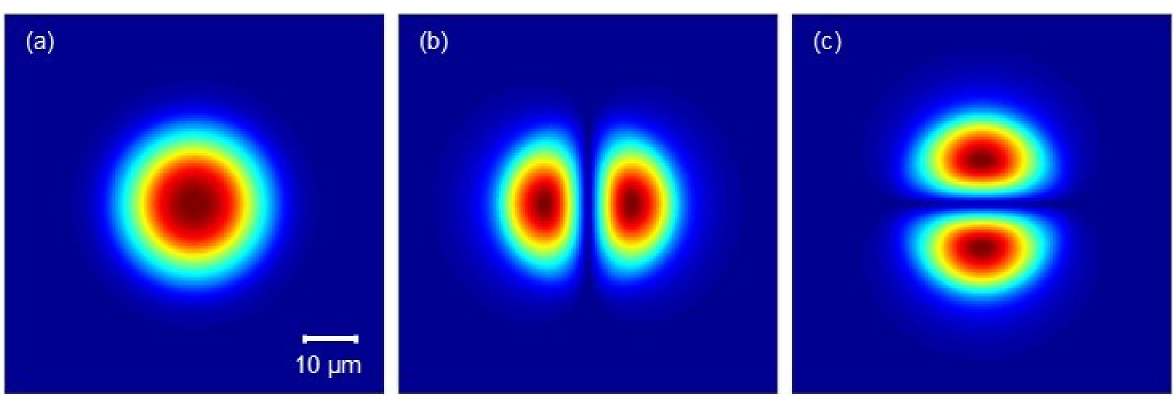


Figure 2. Calculated intensity profiles of LP_{01} mode (a) and even/odd LP_{11} modes (b)/(c) of the fiber shown in Fig. 1.

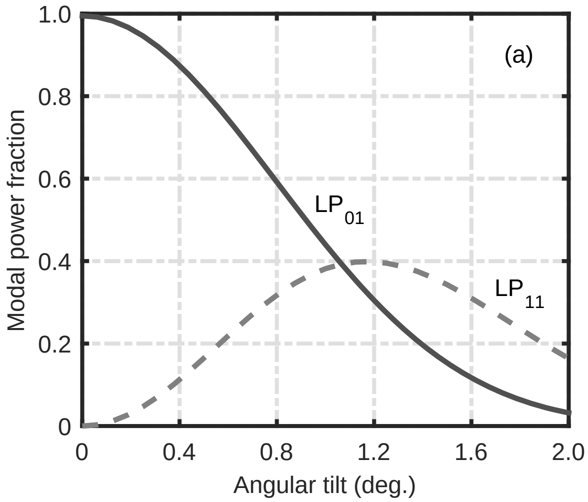


Figure 3. Modal power fractions for LP_{01} and LP_{11} modes versus angular-tilt (a) and lateral-shift (b) coupling misalignments for the fabricated fiber assuming incident mode-matched Gaussian beam.

mode is the only other mode supported by our fiber (see Fig. 2 again). The latter makes easier to achieve effective single-mode behavior at the output of the fiber and loosen somewhat the tolerances on launching conditions, especially in light of the matters discussed in the next paragraph. Excitation of HOMs versus angular-tilt and lateral-shift misalignments for the fabricated fiber are illustrated in Figure 3(a)-(b), assuming incident mode-matched Gaussian beam. Understandably, the sum of relative modal powers of modes guided in the core drops below 1 as excitation of cladding modes becomes increasingly important for ever larger coupling misalignments. From Figure 3 one can see that as much as 40% of the light could get coupled into LP_{11} mode if one is not careful about fiber preparation during the splice process. The latter calls for effective means of suppressing HOMs in order to enforce single-mode propagation in the fiber as mechanical cleaving of large diameter fibers with cleave angle < 0.3º commands great care.

Figure 4(a)-(b) further illustrates the effectiveness of both schemes, namely the bend-induced loss and gain filtering, considering the fiber structure and associated modal intensity distributions shown in Figures 1-2. Differential bending loss between LP_{01} and LP_{11} modes as high as 10 dB/m are readily achieved with reasonable coil diameters (e.g. < 16 cm, see Fig. 4(a)). It is worth mentioning here that HOMs suppression is more pronounced with LP_{11} lobes oriented along the

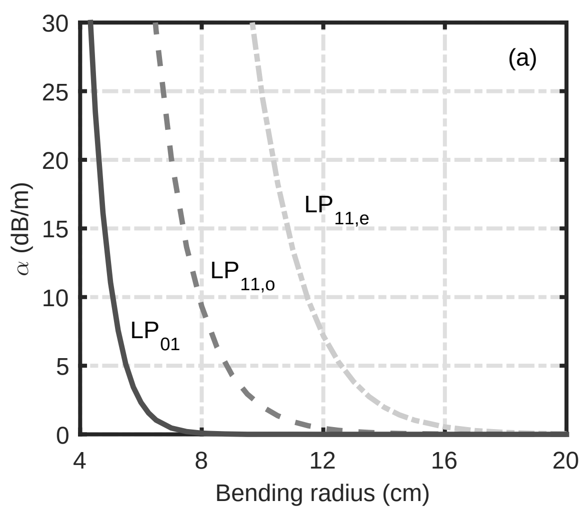


Figure 4. Bend-induced propagation loss (a) and differential gain ratio (b) between LP_{01} and LP_{11} modes for the fabricated LMA fiber.

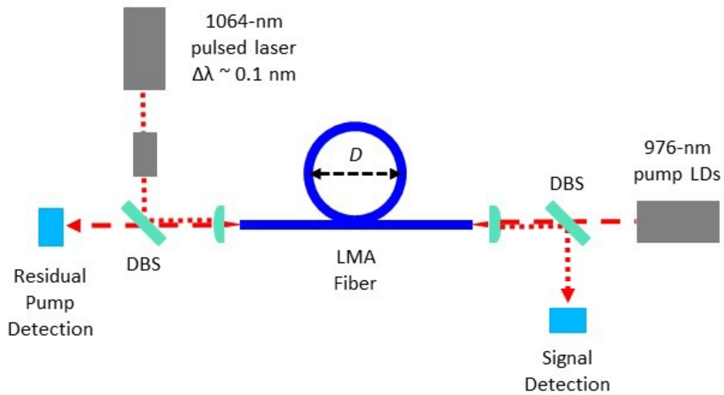


Figure 5. Schematic representation of the experimental setup used to test the LMA fiber.

curvature plane of the coiled fiber (even LP_{11} mode in our case). The significance of preferential amplification is made obvious when one consider the impact of spatial gain saturation (or transverse spatial hole burning) on conventional LMA fiber amplifiers, which is often overlooked. Choosing the proper confinement ratio ensures good gain differential even in case of strong saturation (see Fig. 4(b)), which is in clear contrast with the case of a fiber with uniform core doping, even for intensities well below the saturation intensity I_{sat}. Besides, the contraction of the effective mode area as a result of bend-induced distortion is estimated < 10% when compared to unbent fiber. The bend-induced mode distortion is therefore expected to have little impact on the gain as experienced by the fundamental mode following its delocalization from the region doped with active ions once the fiber is coiled, thus preserving the effectiveness of gain filtering.

3. EXPERIMENTS

The fabricated fiber was tested as a power amplifier following free-space coupling of counter-propagating 976 nm pump and 1064 nm signal beams (see Fig. 5). This way the signal launching conditions could be changed by moving the fiber input termination to check for discrimination of HOMs under various excitation conditions while leaving the pump light coupling unchanged. An obvious drawback is that light that escape from the core, either miscoupled at the launch end or filtered along the coiled fiber, could not be stripped from the cladding at the output and is thus part of the measurements.

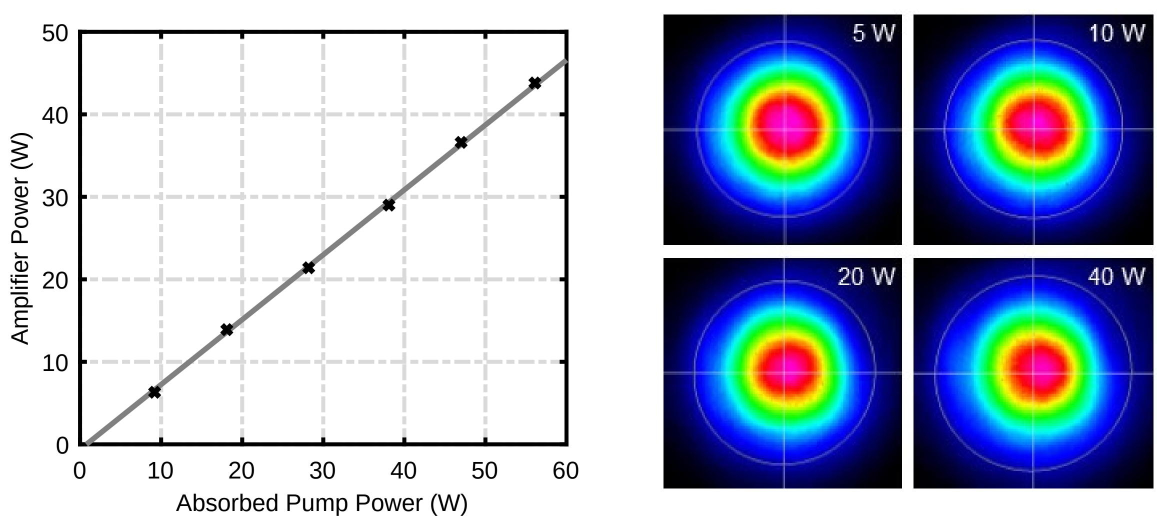


Figure 6. Amplifier slope efficiency curve (on the left) along with far-field beam profiles as measured with a CCD sensor for increasing output power levels (on the right).

Another potential drawback is the fact that the gain saturation is strongest at the amplifier output given the counter-pumping geometry. But the latter turns out to be not much of a concern in our case because of differential gain ratio in favor of the fundamental mode regardless of the saturation level (Fig. 4(b)). The seed linewidth (< 0.1 nm) was chosen such that any coherent superposition of different transverse modes at the output of the fiber could be noticed from the beam properties, especially with regards to beam positional stability as the latter is known to be very sensitive upon intermodal interference. The fiber was coiled on spools of various diameters (10-30 cm) to check how effective HOMs suppression is for various levels of bend-induced losses. Suppression of HOMs became more efficient as differential bending loss increased with tighter coiling, whilst taking care not to induce too much loss on the fundamental mode.

Output average power as high as 40 W was readily achieved, with the latter being only limited by the available pump power (see Fig. 6). Slope efficiency (relative to absorbed pump power) was measured > 78%, meaning that the pump photons are utilized rather efficiently. The saturation energy was measured close to 250μJ at 1064 nm signal wavelength, making this fiber suitable for mJ-level laser systems. Polarization extinction ratio of amplified signal at the output of the fiber was measured > 18 dB. Near Gaussian diffraction-limited output was obtained with beam ellipticity of 0.99 and beam quality factor – M^2 – slightly above 1.1 for both x/y-axis (D4σ method using M^2-200s beam propagation analyzer from Spiricon, see Fig. 7). Exceptional beam quality could be preserved with output power being increased over a full decade, even well over 20 dB of gain. Neither M^2 factor nor beam roundness were seen to change throughout scaling power up to superior limit.

We believe the latter attests to the superior discrimination properties of the fiber design put forward herein. Suppression of HOMs was further tested as we shifted the fiber input termination relative to incident signal beam by as much as ± 15 μm from optimal launch conditions to deliberately excite HOMs. Coupling into LP_{11} mode as high as 30% is expected assuming incident mode-matched Gaussian beam (see Fig. 3(b)). Far-field beam profiles captured for increasingly larger offset launching positions (see Fig. 8) show absolutely no signs of HOMs presence as the beam profile undeniably looks like circular Gaussian LP_{01} mode. Once again, neither M^2 factor nor beam roundness were seen to change as well. Although not shown, a looser coiling was seen to yield increasingly distorted beams and degraded beam quality (with M^2 factor > 1.3 for larger bend radii and outlying launch positions). The offset launching tests were performed along both the slow and fast axis of our amplifier fiber, which incidentally corresponds to orthogonal axes parallel/perpendicular to the coiled fiber. The amplifier output power at maximum offset position only decreased to approximately half the maximum power level because of strong gain saturation. We did make sure also that the amplified spontaneous emission (ASE) did not outgrow the amplified signal at the fiber output as coupling to LP_{01} mode decreased ever more for increasingly larger offset launching positions. Indeed, the ASE fraction was measured below 1 % of the amplifier output power in the worst case, leading us to conclude that the measurements reported herein are accurate.

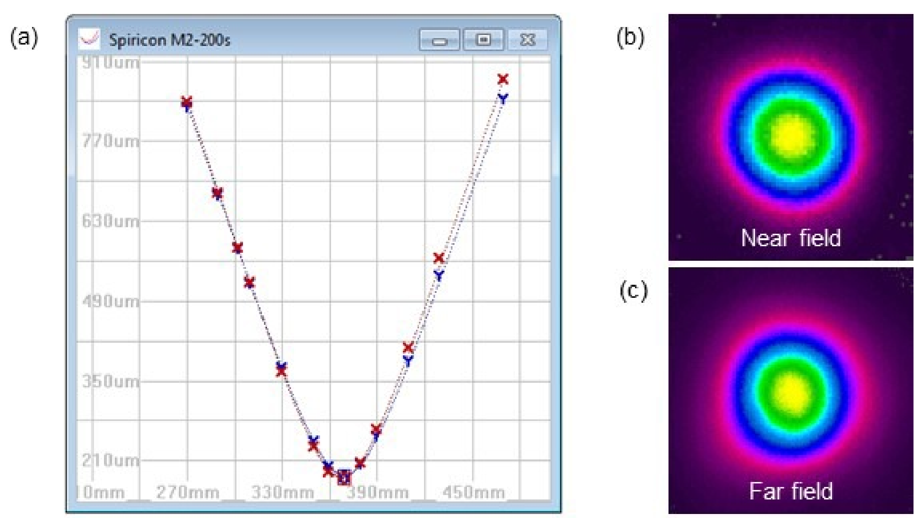


Figure 7. Beam quality factor – M^2 – determination (a) as performed with D4σ method using M^2-200s beam propagation analyzer from Ophir-Spiricon along with near-field (b) and far-field (c) beam profiles.

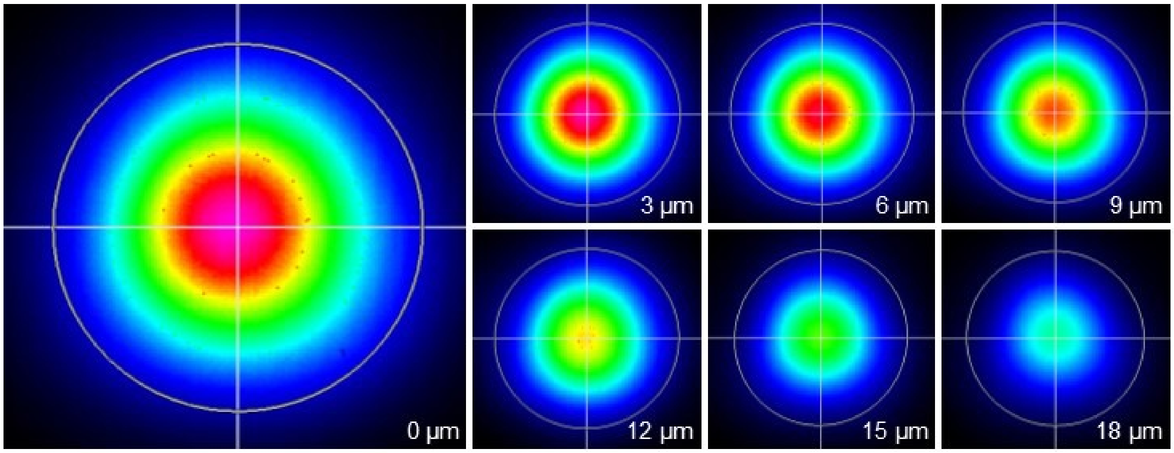
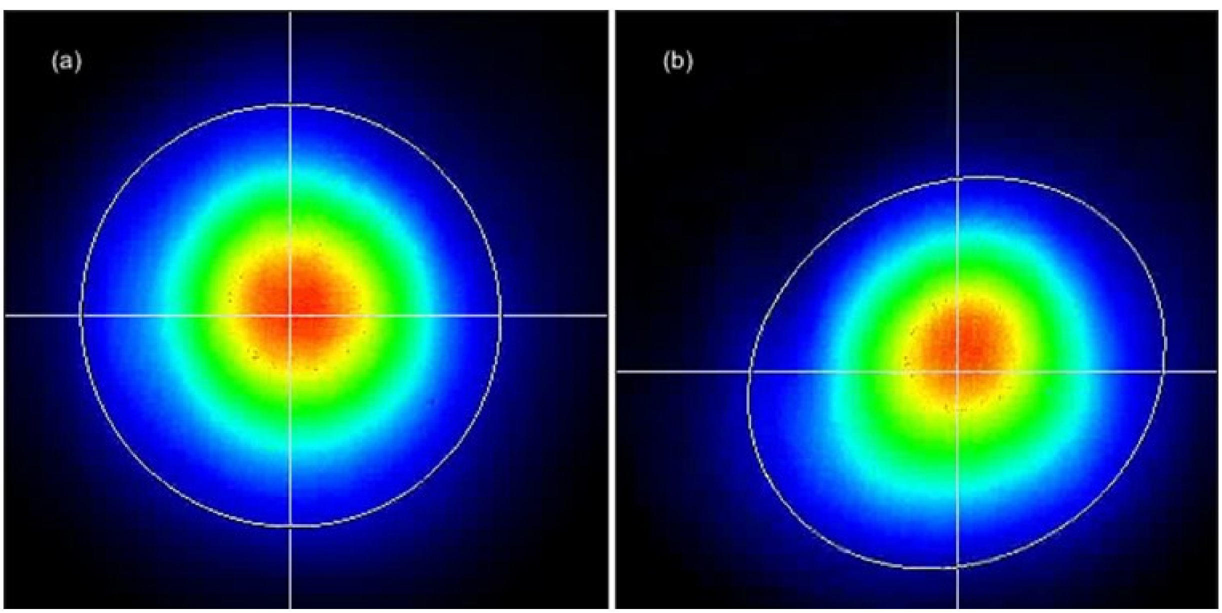


Figure 8. Beam profiles as measured with a CCD sensor for various offset launching positions as the fiber input termination is swept across the incident signal beam starting from optimal launch conditions (offset positions are shown in the lower right corner).

Effective suppression of HOMs in our fiber is perhaps even better illustrated by the beam positional measurements performed from the collimated beam at the amplifier output. In effect, the centroid position of the intensity distribution is known to be very sensitive upon the presence of HOMs in conventional LMA fibers. The coherent superposition of different transverse modes results in beam pointing drifts because of wandering phase changes due to environmental conditions typical of laboratory setting. And the fraction of HOMs need not be large for the pointing to show important drifts. For instance, the centroid position may change by as much as a full beam width for LP_{11} fractions as small as 20 % following half-cycle π radians phase shifts[5].

In consideration of the comments in the paragraph above, we decided to check the beam positional stability at the output of our fiber while at the same time increasing the fraction of excited HOMs, once again by changing the launching conditions in the fiber as described earlier. The effective suppression of HOMs is further evidenced by the beam pointing



Video 1. Beam pointing as measured live with a CCD sensor for both tightly (a) and loosely (b) coiled amplifier fibers as the input fiber termination is successively shifted away from and back toward the optimal launching conditions, with maximum offset launching excursion of 10 µm in both cases. http://dx.doi.org/10.1117/12.2212770

measurements as shown in Video 1(a)-(b), where the drift of the beam centroid in the far-field is shown for both (a) tightly and (b) loosely coiled fibers with identical launching offset excursions (0-10 μm). The difference is striking: while the near single-mode beam of Video 1(a) is barely disturbed (with mean excursion < 10 μm), the presence of HOMs causes the beam centroid to drift over hundreds of microns for distorted beam of Video 1(b). The CCD sensor was positioned 2 m away from the collimated amplifier output. Besides, we believe the random fluctuations observed in Video 1(a) could be attributed to mechanical factors because of the freestanding cantilevered fiber termination as well as other packaging constraints.

4. CONCLUSION

In conclusion, a polarization-maintaining Yb-doped LMA fiber designed and fabricated with depressed-clad and core dopant confinement has been shown to operate effectively as a single-mode waveguide because of strong HOMs suppression. The fiber yields outstanding beam properties when used as a power amplifier even with coherent seed light source. We are confident for the effective mode area of the LMA fiber design proposed herein to be readily scalable over 1000 μm^2 and yet allow for reasonably good beam quality, possibly including built-in mode field adapters made as long tapered sections in the fiber drawing process[10]. Work is ongoing as well to have the rare-earth dopant concentration of the fiber increased to twice the actual level such as to increase absorption and decrease the length of fiber needed to achieve the same performances. The main benefit would be the higher threshold for the onset of detrimental nonlinear effects given the reduced fiber length. The latter obviously requires that the refractive index of the cladding be raised such as to offset the increase of the core refractive index and keep the core NA the same. Finally, advanced modal characterization techniques such as S^2 imaging[11] are being considered in order to assess with greater sensitivity the mode content of our fiber. The latter requires that the measurement be performed while the gain medium is activated, and not as a passive device as is often the case with this type of test, as preferential amplification owing to dopant confinement is integral part of the design.

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