Light propagation with ultralarge modal areas in optical fibers

S. Ramachandran, J. W. Nicholson, S. Ghalmi, M. F. Yan, P. Wisk, E. Monberg, and F. V. Dimarcello

OFS Laboratories, 25 Schoolhouse Road, Somerset, New Jersey 08873

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We demonstrate robust single-transverse-mode light propagation in higher-order modes of a fiber, with effective area A_{eff} ranging from 2100 to 3200 $\mu\mathrm{m}^2$. These modes are accessed using long-period fiber gratings that enable higher-order-mode excitation over a bandwidth of 94 mm with greater than 99% of the light in the desired mode. The fiber is designed such that the effective index separation between modes is always large, hence minimizing in-fiber mode mixing and enabling light propagation over lengths as large as 12 m, with bends down to 4.5 cm radii. The modal stability increases with mode order, suggesting that A_{eff} of this platform is substantially scalable.

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Recent interest in high-power fiber lasers and amplifiers has driven the quest to achieve large-mode-area (LMA) optical fibers that offer robust single-mode operation. The straightforward and conventional means to achieve LMA fibers is to scale the fiber dimensions, but extending such an approach past effective areas (A_{eff}) of $\sim 800\ \mu\mathrm{m}^2$ yields multimode fibers[1] that are susceptible to loss and noise due to mode coupling.[2] Hole-assisted, photonic crystal fibers (PCFs) offer some additional design flexibility by selectively leaking higher-order modes (HOMs),[3] but this approach suffers from the same limitations as conventional fibers, and achievable A_{eff} is currently limited to $\sim 1400\ \mu\mathrm{m}^2$. A variant of PCFs, a rigid glass rod, has gained much recent attention, since a straight light guide can clearly afford one scaling of A_{eff} with low susceptibility to mode coupling.[4] However, such structures negate many advantages of flexible fibers, ranging from long-length devices that enable high-dispersion pulse stretchers/compressors to ease of packaging. Air-guided photonic bandgap fibers may be a promising alternative,[5] since the signal travels in air with negligible nonlinearities, but air guidance negates the possibility of constructing a distributed amplifier by incorporating rare-earth dopants.

Here, we demonstrate a novel platform, using an intentionally multimode fiber where the signal is selectively excited in a single higher-order spatial mode, to show that robust (negligible mode mixing and loss), bend-resistant signal propagation can be achieved in record large mode areas. Our results indicate that signals can be propagated with very high spatial coherence even in highly multimode structures, and this lifts the fundamental restriction on scaling fibers to guide light in increasingly large A_{eff}. We illustrate this with a fiber device with A_{eff} ranging from 2100 to 3200 $\mu\mathrm{m}^2$ that is robust to bending down to radii of curvature of 4.5 cm.

For the extreme A_{eff} values desired for high-power fiber lasers, conventional fibers are slightly multimode even though they are designed for signal propagation in the lowest-order fundamental mode (the so-called LP_{01} mode). This is because increasing the core size to achieve $A_{\mathrm{eff}} > 400\ \mu\mathrm{m}^2$ necessarily leads to a multimode fiber. The stability of these LMA fibers is governed by the extent to which random, distributed, resonant mode mixing between the desired mode and its nearest antisymmetric mode (LP_{1m} mode, where m is the radial mode-order) can be suppressed.[2] This suppression increases with the purity of launch into the desired mode as well as the difference between the effective indices (n_{eff}) of the two modes. The black line in the plot (Fig. 1) illustrates the trade-off between stability (denoted by $n_{0m} - n_{1m}$) and A_{eff} for the LP_{01} mode of conventional fibers. Conventional LMA fibers are limited to $A_{\mathrm{eff}} \sim 800\ \mu\mathrm{m}^2$, because larger A_{eff} yield low enough $n_{01} - n_{11}$ values that mode coupling becomes prohibitively high. The dashed lines in the plot depict this demarcation: while actual values for $n_{01} - n_{11}$ may differ somewhat, based on experimental conditions, we may use this line as a proxy for distinguishing designs that are robust to mode coupling from designs that are susceptible to it. Also shown is a data point denoted PCF, which illustrates the largest A_{eff} ($\sim 1400\ \mu\mathrm{m}^2$) reported in PCFs. While the difference in n_{eff} versus A_{eff} trade-off is similar to the conventional case, PCFs can be designed with large differential modal losses. This enables radiat-

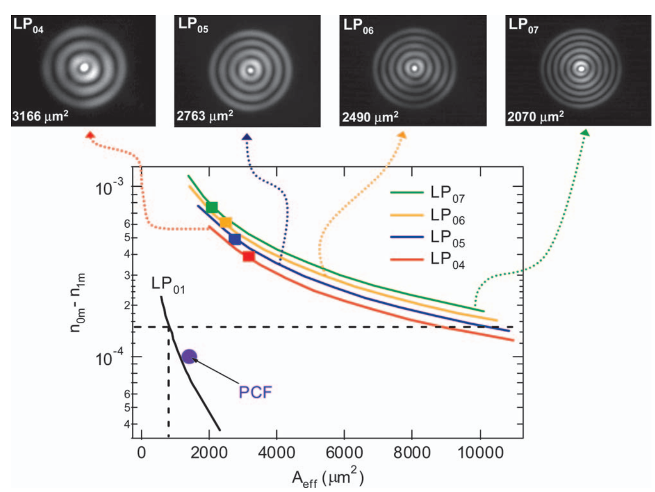

Fig. 1. Effective index difference between nearest neighbors (stability proxy) versus A_{eff}. Mode stability increases with modal order. Top, near-field images after >2 m propagation with 7 cm bends of LPG-excited HOMs with A_{eff} ranging from 2100 to 3200 $\mu\mathrm{m}^2$.

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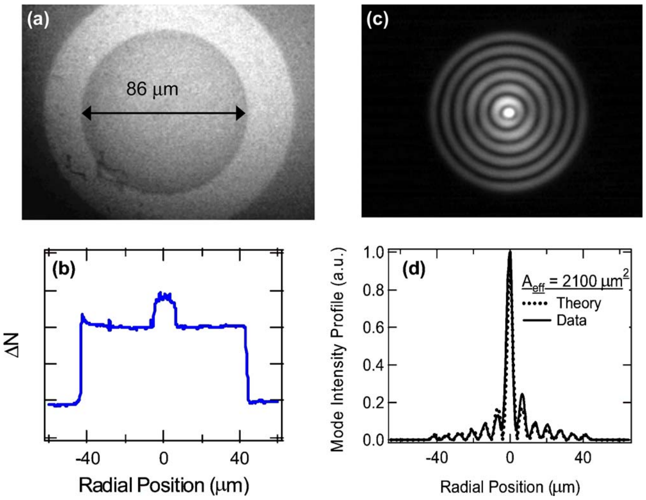

Fig. 2. (Color online) Characteristics of HOM fiber. The horizontal and vertical scales of the images and the horizontal scales of the plots are identical. (a) Near-field image of a fiber facet, showing 86 μm inner cladding. (b) Refractive-index profile of the HOM fiber, with a core similar to SMF and 86 μm inner cladding followed by a downdoped outer trench. (c) Near-field image of the LP_{07} mode at 1600 nm after 12 m propagation with 4.5 cm radius bends. (d) Intensity line scan of (c) and theoretical profile: $A_{eff} \sim 2100\ \mu m^2$.

ing out the LP_{11} mode, yielding higher modal purity at the output. Hence these fibers relax the constraint on conventional fibers and can offer stable operation for cases with significantly lower $n_{01}-n_{11}$ values. Nevertheless, it is evident that conventional or photonic crystal LMA fibers are inherently limited by the trade-off between stability and A_{eff}.

In contrast, operating in the HOM presents a unique design space to scale A_{eff}. The colored curves in Fig. 1 show the stability ($n_{0m}-n_{1m}$) versus A_{eff} for four different LP_{0m} modes ($m>1$ denoting HOMs) in a specially designed, intentionally multimode fiber [index profile shown in Fig. 2(b)]. While they exhibit a stability versus A_{eff} trade-off as do the conventional LP_{01} modes, they dramatically differ on two accounts. First, the $n_{0m}-n_{1m}$ values for HOMs are an order of magnitude higher than those for the LP_{01} mode, indicating the ability to obtain stable, mode-mixing-free signal propagation with significantly larger A_{eff}. More important, the $n_{0m}-n_{1m}$ values increase with modal order m, indicating that this concept is substantially scalable. This is a highly counterintuitive result that challenges the conventional wisdom that fibers must be single mode for robust signal propagation. However, the results in this plot, combined with an in-fiber grating designed to selectively couple to only the desired mode, dramatically open up this design space. The mode images shown in Fig. 1 are experimentally recorded near-field images of the grating-excited LP_{04}, LP_{05}, LP_{06}, and LP_{07} modes, respectively, in a HOM fiber, with A_{eff} ranging from $\sim 2100\ \mu m^2$ (for the LP_{07} mode) to $\sim 3200\ \mu m^2$ (for the LP_{04} mode). The mode images were obtained after propagation through more than 2 m of fiber, with bends with a radius of curvature of at least 7 cm. The mode profiles clearly illustrate HOM propagation with very high modal purity and represent what we believe to be the largest demonstrated A_{eff} in fibers that are bend resistant.

Figure 2 shows the details of our fiber and one of the HOMs (the LP_{07} mode). The near-field image of the fiber facet [Fig. 2(a)] and the corresponding refractive index of the profile [Fig. 2(b)] show that the design comprises a core similar to those of single-mode fibers (SMFs), followed by an inner-clad region of 86 μm diameter and a downdoped protective trench. Figure 2(c) shows the recorded near-field image of the grating-excited LP_{07} mode after ~12 m of propagation at 1600 nm, and Fig. 1(d) compares a corresponding intensity line scan with the theoretically predicted mode profile. The mode-intensity profiles are used to calculate A_{eff} of the mode, given by $A_{eff}=(\int I\, dA)^2/\int I^2\, dA$, yielding 2140 μm^2 for the simulation and 2075 μm^2 for the experiment. The excellent match between experiment and theory validates the simulations shown in Fig. 1, on the basis of which we claim that this platform is scalable in A_{eff}. An attractive feature of this platform is its wavelength-agnostic nature. Simulations reveal that for $\lambda = 1050$ nm A_{eff} is 1980 μm, which is only 6% smaller than the value at 1600 nm. This is because, unlike the LP_{01} mode in a LMA core, the HOM has a negligible evanescent tail past its waveguiding boundary—the inner-clad-to-trench boundary.

A critical component of this device is a long-period fiber grating (LPG), which excites the desired HOM, as shown-in the schematic in Fig. 3(a). The signal is first coupled into the SMF-like core of the HOM fiber [see the fiber profile in Fig. 2(b)], such coupling can be achieved with very high modal purity and low loss using conventional splices. Thereafter, the signal is converted to the desired LP_{07} mode with a 2 cm LPG whose conversion efficiency η is shown in Fig. 3(b) ($\eta > 99\%$ over a 94 nm bandwidth, with peak $\eta \sim 99.93\%$). The extreme efficiencies and broad bandwidths are enabled by the dispersive design of the LP_{07} mode.[6,7] The resonant nature of this coupler ensures that the incoming signal is coupled only to the desired LP_{07} mode. Since gratings are reciprocal devices, an output LPG would convert the signal back to a Gaussian shape.

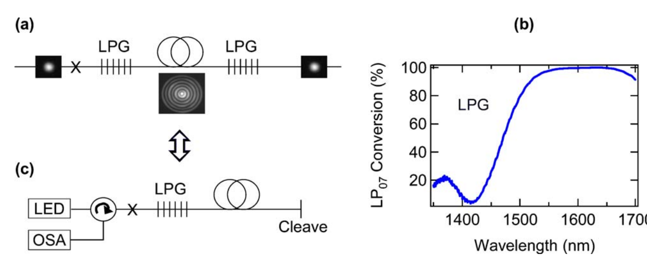

Fig. 3. (Color online) (a) Device schematic: light is coupled into and out of HOM with LPGs whose conversion efficiency is shown in (b). LPG, broadband coupling with efficiency $\eta > 99\%$ over 94 nm, with peak coupling as high as 99.93%. (c) Alternative schematic for characterizing HOM fiber: the cleave serves to fold the device propagation path so that the single LPG acts as both input and output LPGs. X, splice; OSA, optical spectrum analyzer.

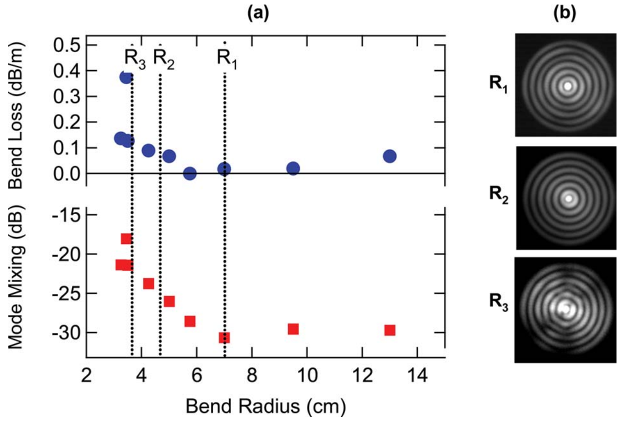

Fig. 4. (Color online) HOM propagation characterization in 3 m long fiber as shown in Fig. 3(c). (a) Excess bend loss (top) and mode-mixing efficiency (bottom) versus bend radius. (b) Near-field images for bend radii $R_1=7$ cm, $R_2=4.5$ cm, $R_3=3.8$ cm. There is no change for $R>7$ cm; there are distortions for $R<4$ cm. Modal output is stable down to $R\sim4.5$ cm.

While the desired operation of this device would utilize the schematic in Fig. 3(a), characterizing the performance of the device is facilitated by having access to the HOM; hence, for measuring loss, mode mixing, and modal distortions (described below), we use the equivalent schematic shown in Fig. 3(c). The cleave serves to backreflect the signal through the device, which is reconverted by the input LPG into the LP_{01} mode. This backreflected light is then routed through the circulator for spectral and loss measurements.

Figure 4(a) is a plot of the excess bend loss (top) and mode-mixing level (bottom; the mode-mixing level shown in dB indicates the fraction of light in unwanted modes), as a function of bend radius, measured on a 3 m segment of the HOM fiber. The mode-mixing level was measured by recording the amplitude of fluctuations in the transmitted intensity; since mode mixing leads to simultaneous propagation of several modes, spectral interference at the output enables accurate determination of the ratio of power in different modes.[8] For bend radii >7 cm the signal experiences immeasurably low bend losses, and mode-mixing levels remain below −30 dB (0.1%), consistent with the fact that the LPG had ~99.93% conversion efficiency. Thereafter, down to a bend radius of ~4 cm, the bend losses as well as mode-mixing amplitudes increase slowly, indicating the onset of small amounts of loss/mode coupling. For bend radii <4 cm, the losses as well as the mode coupling increase rapidly. This is consistent with near-field images of the modal output recorded in the bent fiber. Figure 4(b) shows such images for bends of 7, 4.5, and 3.8 cm, respectively. While modal images for bend radii down to 4.5 cm yield a pure LP_{07} output, that of the fiber bent to $R_3=3.8$ cm shows distortions, presumably due to unwanted coupling to other HOMs. The total insertion loss of this fiber schematic, including input splice, LPG, and propagation in the HOM fiber, was <0.2 dB.

One potential drawback of this platform is that the signal travels for a short distance in the (smaller A_{eff}) LP_{01} mode, which is potentially susceptible to nonlinearities. We expect this issue to be resolvable for several reasons. First, total length-scales over which the signal resides in the LP_{01} mode can be subcentimeter, since LPGs with lengths as short as 0.5 cm can easily be realized (short LPGs will yield the additional benefit of greater bandwidth). Second, cores with very large A_{eff} for the LP_{01} can be designed in this fiber; this core can be substantially larger than those of conventional LMA fibers, because only centimeter or millimeter propagation lengths are required in the LP_{01} mode. The combination of large A_{eff} and subcentimeter lengths for the LP_{01} mode should substantially minimize any nonlinearities due to them. In addition, for output power levels that will not even withstand the aforementioned cores, one could simply output the mode in the HOM and use free-space phase plates to convert them to any desired output shape (including Gaussian); see Ref. 9 for an example of such devices. This is feasible because the HOM is strictly spatially coherent, and hence can be relayed through lenses or spatially transformed with diffractive-optic elements, in free space.

In summary, we have shown that the higher-order modes in a fiber offer orders-of-magnitude higher design flexibility for obtaining signal propagation in ultralarge modal areas in a fiber. Our demonstration of stable, bend-resistant, long-length signal propagation in modal areas ranging from 2100 to 3200 μm^2 represents an improvement by a factor of 2 to 4 over A_{eff} of alternative fibers that also offer robust bend-resistant light propagation. More importantly, this concept appears to offer substantial scalability in achievable A_{eff}, because the mode stability actually increases with mode order.

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