Extending Effective Area of Fundamental Mode in Optical Fibers

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(Invited Paper)

***Abstract*—High power fiber lasers have become well established in many commercial realms. However, the amplification of ultrafast pulses to higher pulse energies in ytterbium-doped fibers remains very challenging due to nonlinear effects. We have demonstrated a new class of optical fibers based on resonantly enhanced leakage channels to extend the effective mode area of conventional single mode fibers by over two orders of magnitudes. This new class of fibers paves the way for a new breed of diffraction-limited kW-level ultrafast lasers, which can usher in a new age of high peak and average power ultrafast laser science as well as many new industrial applications in material processing.**

***Index Terms*—Optical fiber amplifiers, optical fiber lasers, optical fibers.**

I. Introduction

HIGH power fiber lasers are increasingly substituting solid state and gas lasers in the commercial realm [1]–[3]. Driven by continued progress in the development of large core fibers, the high peak power handling capabilities of fiber lasers are also becoming increasingly attractive. Indeed, ytterbium fiber lasers have recently made forays into the field of high field physics based on the increased output of nonlinear phenomena made possible with high average power ultrafast fiber pump lasers [4], [5]. Fiber lasers can operate at very high optical efficiency and their geometry allows for straight forward heat removal, enabling very compact construction. Moreover, their superior mode quality at high average powers is opening up new applications such as remote laser welding and coherent addition which were previously not considered practical with conventional laser technology. As the power from fiber lasers is continuously going up, nonlinear effects need to be overcome for further power scaling.

The most straight-forward way to increase the nonlinear limits of fiber technology is via an increase in mode-diameter. This, however, quickly leads to multimode operation in optical fibers. To avoid multimode operation in a conventional optical fiber, the numerical aperture, $\mathrm{NA} = \left(n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2\right)^{1/2}$ needs to be lowered, where n_{co} and n_{cl} are fiber core and cladding index respectively. The NA is currently limited to ~ 0.06 by the index accuracy which can be reliably controlled in a fabrication process. This corresponds to a single mode core diameter of ~ 13 μm at a wavelength of ~ 1 μm. It has been shown that reasonable single mode operation can be achieved in a fiber which supports few modes, if appropriate efforts are made to minimize excitation of higher order modes [1] and coiling is used to introduce differential mode loss [6]. This approach can extend reasonable single mode operation to core diameters up to 30 μm.

Beyond this point, an increase in mode area is ultimately limited by increased difficulties in selectively launching the fundamental mode as well as inter-modal coupling, which would drain energy from the desired mode. Recently photonic crystal fibers (PCFs) have been able to demonstrate single mode operation in much larger core diameters of up to 100 μm [7], by effectively reducing NA beyond the conventional fiber limit by using an ytterbium-doped core glass with a closely matched refractive index to that of the cladding glass and by introducing small air-holes into the cladding to slightly reduce the effective refractive index of the cladding. The extremely small NA of these PCFs makes them extremely weakly guided; therefore such fibers need to be kept straight for core diameters above 45 μm. However, by using rods of few millimeters in diameters [3], the macro- and micro-bending in 100 μm core PCFs can be made to be manageable [7]. The rods are also multi-mode in nature and provide little higher-order mode suppression. Consequently, precise input mode matching is still necessary. Moreover, mode quality is further reduced by the required procedure to seal the air holes at the fiber ends for long-term reliability. Propagation of higher order modes in a highly multimode fiber has also been proposed as a means to extend effective mode area. Mode converters are required in this case for both input and output ends of the fiber. High gain amplifiers have not yet been demonstrated with this approach [8]. Chirally coupled core fiber has also been proposed recently to extend effective mode area [9]. Higher order modes can be made to have high losses by making them to be resonantly coupled to a helical core placed adjacent to the signal core. Robust single mode in core diameter of 35 μm has been demonstrated. Further scaling of core diameter would have to overcome the reduction of overlap between modes in the two cores which enables efficient mode coupling, and is still to be demonstrated.

Large core fibers are particularly useful for the generation of high peak power pulses at large average powers. On one hand,

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large core fibers extend the nonlinear limits of fiber technology and on the other hand, large core fibers also increase energy storage. As in any gain medium, the extractable pulse energy is ultimately limited by the number of excited active ions, which scales with the volume of glass doped. Although the stored energy can be increased by increasing active ion concentration, this is, however, limited by the onset of ion clustering.

Ultimately the most challenging application of large core fibers is in the amplification of ultra short pulses. In the ultrafast domain, the chirped pulse amplification method [10] is generally used. The peak power of chirped amplified pulses in fibers can generally not exceed the self-focusing limit of around 6 MW [11]–[13]; moreover the fiber amplifier bandwidth ultimately determines the obtainable pulse widths. At least in ytterbium-doped optical fibers, the amplified bandwidth is maximized for low values of amplifier inversion. In turn the gain per unit length is around 10 times lower than the peak gain for wide bandwidth operation, requiring a ten times longer amplifier length. On the other hand wide bandwidth operation is essential for applications in hyperspectral broadening such as coherent THz [14] and XUV [4], [5] generation which are greatly limited by currently available fiber amplifier technology.

In this paper, we will demonstrate both theoretically and experimentally a new class of optical fibers, resonantly enhanced leakage channel fibers (LCFs). LCFs differ from conventional optical fibers by breaking up the continuity of the core and cladding boundary. This broken boundary at the core and cladding interface in a LCF effectively ensures that total internal reflection cannot be satisfied everywhere along the core and cladding boundary, unlike in a conventional optical fiber, and, consequently, makes the waveguide leaky for all modes. An critical new design feature, where the second mode is made to resonate with the outer cladding of the fiber, increases the higher-order mode suppression by a further order of magnitude, rendering the resonantly enhanced LCF essentially behaving as a conventional single mode optical fiber. These unique properties of LCFs enable them to be precisely engineered to have high confinement loss for all higher order modes and low confinement loss for the fundamental mode, *effectively extending fundamental mode effective area of a conventional single optical fiber by two orders of magnitude*. In other words we exploited the increased ability of higher order modes to leak through small gaps in the core and cladding boundary while maintaining good fundamental mode confinement, a concept well explained by Russell in [15]. Moreover, this new class of fibers is entirely made of glasses, much like conventional optical fibers and unlike PCFs with air holes. This enables them to be fabricated on a highly reproducible basis and to be cleaved, spliced, tapered and handled in a way akin to conventional optical fiber.

This new class of all glass resonantly enhanced LCFs, can potentially extend the power limits of ultrafast fiber lasers by more than two orders of magnitude compared to conventional fiber technology and will usher in a new era of high power ultrafast laser science. Moreover, the unprecedented peak power and pulse energy limits of LCFs will have a profound impact on commercial fiber lasers as the key enabling technology for many new applications in material processing and micro-machining.

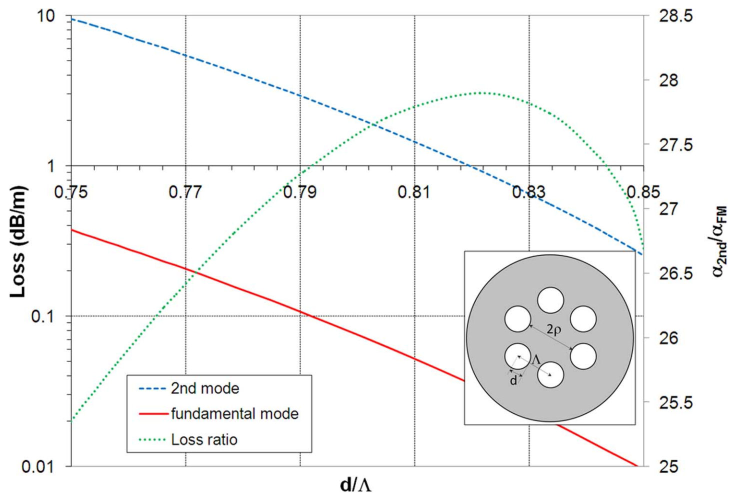

Fig. 1. Confinement loss and loss ratio of fundamental and second order mode in a LCF with $2\rho = 50\ \mu$m and a refractive index contrast, $\Delta n = n_{\rm b} - n_{\rm f} = 1.2 \times 10^{-3}$ at $\lambda = 1.05\ \mu$m.

II. Theoretical Background

The cross section of a LCF with six circular low index cladding features is shown in the inset of Fig. 1. Λ is the center-to-center separation and d/2 is the distance from the center of a feature to its side along a line linking centers of two nearest neighbors. The core diameter 2ρ is defined as the minimum distance between two opposing features. The structure is analyzed with a multi-pole mode solver developed at IMRA America, similar to that described in [16]. The simulated fundamental mode confinement loss, $\alpha_{\rm FM}$, and second higher order modes loss, $\alpha_{\rm 2nd}$, are shown in Fig. 1 for a fiber with $2\rho = 50\ \mu$m and a refractive index contrast, $\Delta n = n_{\rm b} - n_{\rm f} = 1.2 \times 10^{-3}$, where $n_{\rm b}$ and $n_{\rm f}$ are refractive index of background glass and cladding features respectively. The first set of higher order modes includes three slightly non-degenerate higher order modes, TE01, HE21 (consists of two degenerate modes) and TM01 and they all have very similar confinement losses [2]. The next set of higher order modes has two slightly non-degenerate modes of well over one order of magnitude higher confinement losses. It is usually sufficient just to consider the first set of higher order modes in a LCF in the context of designing LCFs for robust single mode operation [2]. Confinement loss for all modes decreases as d/Λ gets larger. In the following analysis all reference to loss is expressed in dB/m.

One important feature of the LCF in Fig. 1 is that a very small refractive index contrast of 1.2×10^{-3} is used. The features are typically made of fluorine-doped silica. This enables the LCF to be made entirely of glass and to be handled in the same way as a conventional optical fiber, while providing sufficient differential mode loss between fundamental mode loss and second mode loss, $\alpha_{\rm 2nd} > 25 * \alpha_{\rm FM}$, over the entire range of d/Λ studied. Loss ratio, $\alpha_{\rm 2nd}/\alpha_{\rm FM}$, changes by less than 10% over the entire range and peaks at 27.9 at $d/\Lambda = 0.82$ for this LCF with $2\rho = 50\ \mu$m. This makes loss ratio a useful parameter to use when designing LCF.

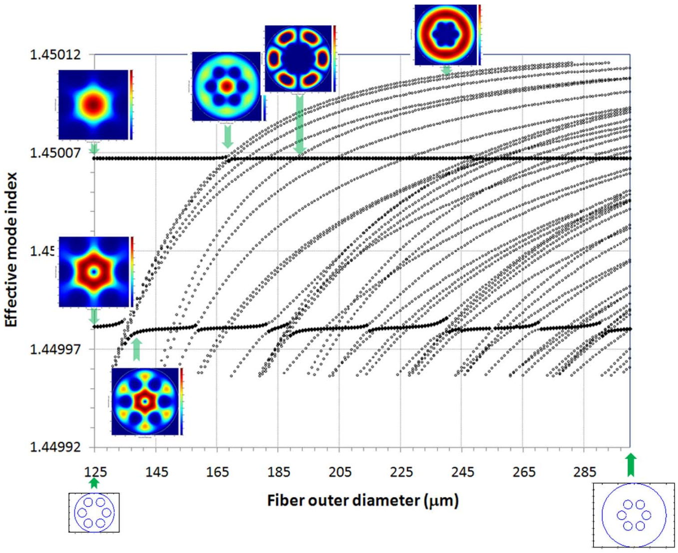

Fig. 2. Effective index of modes in a double clad LCF with $2\rho = 50\ \mu$m, $d/\Lambda = 0.7$, $\Delta n = 1.2 \times 10^{-3}$ and $n_{\text{coating}} = 1.37$ at $\lambda = 1.05\ \mu$m.

The analysis in Fig. 1 is performed considering a waveguide formed by six circular features in an infinite background glass. In reality, there is a finite fiber diameter and additional coatings on the optical fiber. There are typically two types of coatings used. A high index polymer coating is typically employed for standard optical fibers and a low index coating is used to form a double clad fiber which supports a multimode pump within the low index coating. In case of LCFs, there is a strong optical coupling between the core formed by the six low index features and the second cladding region beyond the six low index features. A deeper understanding of LCFs requires a study of the overall fiber with coating included. For high average output powers, a high power multimode pump is usually deployed in combination with a double clad fiber. An example of a double clad fiber is a LCF with low index polymer coating where a multimode pump is guided within the low index coating while a single spatial mode laser beam is guided in the core doped with active ions. Many modes are guided in a double clad LCF when considering the overall fiber. Fig. 2 tracks a number of lower order modes for a LCF with $2\rho = 50\ \mu$m, $d/\Lambda = 0.7$, $\Delta n = 1.2 \times 10^{-3}$ and $n_{\text{coating}} = 1.37$, while varying fiber outer diameter. The Refractive index of the background silica glass is simulated by empirical formula given in [17] at $\lambda = 1.05\ \mu$m.

The Fundamental core mode is represented by red dots (top dark curve) and the second core mode by blue dots (lower dark curve), respectively. All the other modes are represented by black circles. The first point to note is that the fundamental core mode is no longer the fundamental mode (the mode with largest effective index) of the fiber at larger fiber diameters, which is a mode with most of its power in the second cladding region beyond the six low index features. In other words, the fundamental core mode is just another higher order mode of the fiber, which happens to resemble a Gaussian beam in the core. The second point to note is that there are strong anticrossings, where strongly interacting modes take on each other's features, e.g., a fundamental core mode at $\sim 170\ \mu$m or a second core mode at $\sim 135\ \mu$m (see insets in Fig. 1 for modes), and weak anticrossings, e.g., fundamental core mode at $\sim 195\ \mu$m (see inset for mode), where the concerned modes share very little common features in practice (only share significant amount of each other's features over a practically non-existent extremely narrow range). A third point to note is that there are many more strong anticrossings for the second core mode. Strong anticrossing is interesting, because the mode can have a larger part of its power in the cladding where there is no gain and, more importantly, the increased reliance on the glass and coating boundary for its guidance makes it more vulnerable to power leakage to coating and higher order modes through macro and micro bending as well as perturbation-induced coupling at the glass and coating interface. If a fiber diameter is chosen such that the second core mode is at a strong anticrossing, further higher order mode suppression and much improved single mode operation in the core can be achieved.

In a double clad LCF with low index coating, all guided modes are theoretically lossless, i.e., there is total internal reflection for the large number of guided modes at the glass and coating boundary. Though all modes are guided in this case, the modes which derives significant part of its guidance from glass and coating interface and less of their guidance from the inner cladding features are much more susceptible to macro and micro bending due their much large spatial presence and to glass and coating interface imperfections. This will effectively remove power away from these modes and reduce their effective propagation distance in the core, effectively rendering them lossy. Robust single mode operation in the core in this case implies that adequate core guidance is only possible for the fundamental core mode. In case where the core is doped with active ions, only the fundamental core mode will be strongly amplified. This is not, however, a critical factor in higher order mode suppression.

While all guided modes are lossless in a LCF with low index coating, all modes are leaky in a LCF with high index coating and modes which rely strongly on low index coating and less on the inner cladding features for its guidance will leak out quickly. Confinement loss, in this case, provides a good measure of how much a mode is guided by the inner cladding features, and, consequently, of mode discrimination in propagation. A significant part of the respective mode features remain unchanged when the higher index coating is replaced by a lower one, and, consequently, the analysis for the case of high index coating provides a good measurement in terms of mode robustness for the case of low index coating in a double clad fiber. The confinement losses of the same LCF with a high index coating of $n_{\text{coating}} = 1.54$ and $\lambda = 1.05\ \mu$m is shown in Fig. 3. Modes higher than second mode, in general, have much higher loss and do not need to be considered in practice [2]. The peaks in the confinement loss are from strong anticrossings. They remain at the same locations as those in Fig. 2 with low index coating. It can be clearly seen that a significant increase of mode discrimination can be achieved by operating at a strong second core mode anticrossing. A LCF operating at the strong second core mode anticrossing at a fiber diameter of 268 μm is further studied in Fig. 4, where confinement losses are simulated for a range of wavelengths. The wavelength dependence of loss is influenced by the resonant nature of the design. It can be seen that a loss ratio, $\alpha_{2\text{nd}}/\alpha_{\text{FM}}$, as high as 337

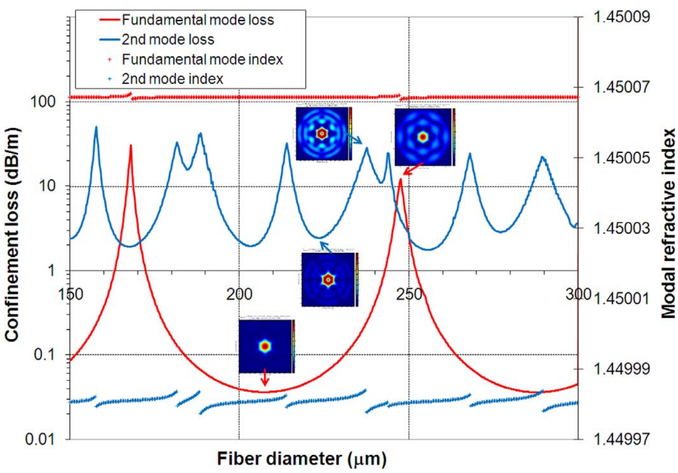

Fig. 3. Confinement loss and modal index of fundamental and second order mode in a LCF with $2\rho = 50\ \mu\mathrm{m}$, $d/\Lambda = 0.7$, $\Delta n = 1.2 \times 10^{-3}$ and $n_{\mathrm{coating}} = 1.54$ at $\lambda = 1.05\ \mu\mathrm{m}$.

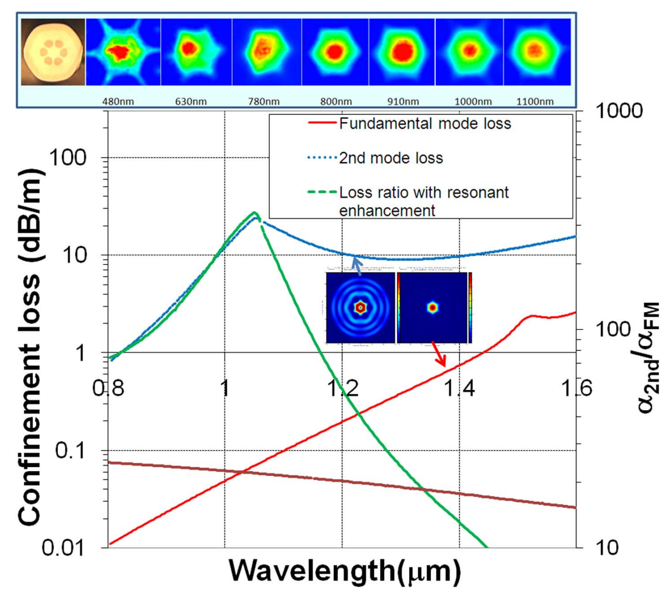

Fig. 4. Confinement loss and loss ratio of fundamental and second order mode in a LCF with $2\rho = 50\ \mu\mathrm{m}$, $d/\Lambda = 0.7$, $\Delta n = 1.2 \times 10^{-3}$ and $n_{\mathrm{coating}} = 1.54$ at a fiber outer diameter of 268 μm. Fiber cross section and measured modes at the output of a 20 cm fiber at various wavelengths are given at the top for LCF1 ($2\rho = 52.7\ \mu\mathrm{m}$, $d/\Lambda = 0.8$, a coating with $n_{\mathrm{coating}} = 1.37$ and flat-flat outer glass diameter of 254.2 μm).

is achieved at $\lambda = 1.05\ \mu\mathrm{m}$ and $\alpha_{\mathrm{2nd}}/\alpha_{\mathrm{FM}}$ is larger than 100 well over a range of two hundred nanometers, representing at least an order of magnitude improvement over standard LCFs.

It should be noted that any resonant effects are dependent on environmental effects, such as temperature and external stress. This is, however, not expected to be an issue especially for the fundamental mode due to the weak wavelength dependence shown in Fig. 4. It should also be noted that deliberate designs of a second guiding structure in resonance with higher order modes guided in the core have also been proposed recently for the suppression of higher order mode propagations in the core [18], [19].

III. Experiments

A large number of LCFs with various core diameters, from 30 to 180 μm, and d/Λ, 0.7 to 0.9, were fabricated using the well known stack-and-draw technique, where rods of the same diameters are stacked hexagonally to form a bundle and the bundle is then inserted into a tube to be drawn into fibers with appropriate atmosphere and vacuum control inside the tube. An ytterbium-doped fiber, LCF1, was also fabricated. The LCF1 has $2\rho = 52.7\ \mu\mathrm{m}$, $d/\Lambda = 0.8$, and a coating with $n_{\mathrm{coating}} = 1.37$. Flat-flat outer glass diameter is 254.2 μm and the effective mode area is calculated to be 1548 $\mu\mathrm{m}^2$ with measured pump absorption of ~ 11 dB/m at 976 nm. The center $\sim 70\%$ of the core is doped with ytterbium ions. The ytterbium-doped glass was made with a specially developed process to produce a glass with excellent refractive index uniformity, $< 1 \times 10^{-4}$, and precise average refractive index match to the rest of the fiber, $< 5 \times 10^{-5}$. This is very important for preserving the desired mode pattern as well as robust single mode operation.

In a first test of robustness of single mode propagation of LCF1, the output of a 6 m fiber coiled loosely in a ~ 50 cm coils was collimated and imaged by a CCD camera while input condition was adjusted. Note that LCF1 is a double clad ytterbium-doped fiber, but in this experiment the fiber was used in an unpumped configuration. Nevertheless the output mode pattern was stable and no higher order mode was observed even when launch condition was adjusted far from optimum, proving indeed that the higher-order modes had a much higher propagation loss even in an unpumped double clad amplifier fiber. The output mode pattern was stable and remained fundamental mode while the fiber was handled by pressing and bending between two fingers. To characterize the wavelength dependence of propagation, the output modes in a wavelength range from 480–1100 nm after propagation of a super-continuum source through a 20 cm long LCF1 were captured by a CCD and are shown in the top inset of Fig. 4. The silicone CCD does not work beyond 1100 nm. Clear broad band single mode operation is evident above 800 nm while there are increasing signs of higher order mode content towards shorter wavelength below 800 nm. Fig. 4 shows that the simulated second order mode gets increasingly transmitted towards shorter wavelength reaching a loss of ~ 1 dB/m at 800 nm for this theoretical LCF with 50 μm core. Despite the fact that LCF1 has low index coating while the simulated fiber has high index coating, the simulation seems to provide a good agreement with the experiment.

Design issues of large core LCF are discussed in [2], [20]. LCF2, shown on the top left inset in Fig. 5, has $2\rho = 101\ \mu\mathrm{m}$, $d/\Lambda = 0.9$ and a coating with $n_{\mathrm{coating}} = 1.54$. The effective mode area of LCF2 was calculated to be 5117 $\mu\mathrm{m}^2$. A length of LCF2 ~ 6 m long was loosely coiled in a 1 m coil. The Measured M^2 with an ASE source and Spiricon $M^2 - 200$ is $M_{\mathrm{x}}^2 = 1.26$ and $M_{\mathrm{y}}^2 = 1.29$. M^2 is commonly used for beam quality measurement. A M^2 value of 1 corresponds to a 'perfect' Gaussian beam profile, with all practical beams having an M^2 value > 1. LCF3, shown on the bottom left inset, has $2\rho = 183.3\ \mu\mathrm{m}$, $d/\Lambda = 0.8$ and a coating with $n_{\mathrm{coating}} = 1.54$. A conventional single mode optical fiber of the same scale is also shown for comparison. The effective mode area of LCF3 is

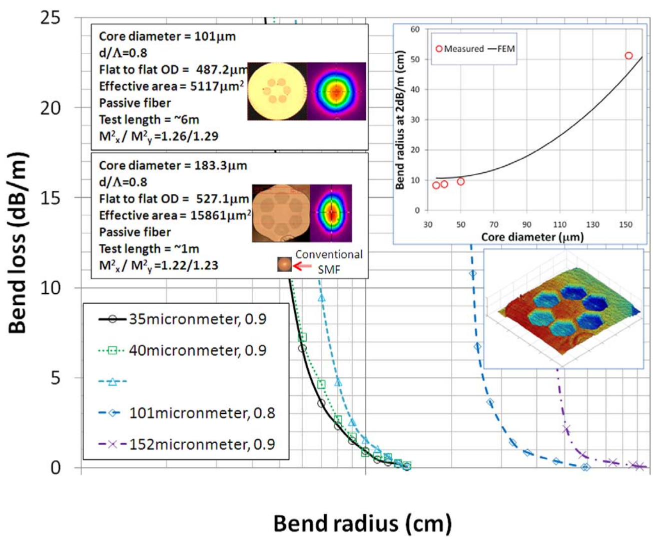

Fig. 5. Cross section, measured mode and fiber details are given for LCF2, left inset, and LCF3, right inset. Both fibers have coating index of 1.54. Measured bend loss for LCFs with various core diameters.

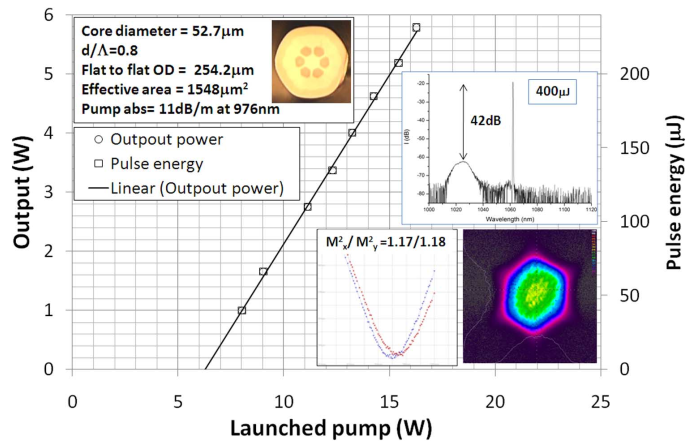

Fig. 6. Performance of an fiber amplifier built with 3 m LCF1. Slope efficiency is 57%.

calculated to be 15861 μm^2, a record effective mode area and over two orders of magnitude improvement over conventional single mode optical fiber. The Measured M^2 of a 1 m straight fiber with an ASE source is $M_{\rm x}^2 = 1.22$ and $M_{\rm y}^2 = 1.23$. Measured mode pattern at the output of the fibers are also shown in Fig. 5. Mode, in general, is more sensitive to external stress on the fiber at very large core diameters, leading to the distortion on the mode pattern.

Fig. 5 also summarizes bend loss measurements in LCFs with core diameters of 35 μm, 40 μm, 50 μm, 101 μm and 152 μm respectively. The fiber was first laid in a prefabricated circular grooves with various diameters. Transmission at each coil diameters was then measured after the output mode pattern was confirmed. Absolute transmission of the fibers was measured by a separate cut-back measurement. The absolute transmission was then used to re-calibrate the relative bend loss measurement. The ability of LCFs to be bent diminishes very quickly as the core diameter increases. This effect is fundamentally related to the fact that the ability of guided modes to navigate a bend is related to how rapidly a mode can change its spatial pattern without breaking up while propagating, i.e., maintain adiabatic transition. As the mode gets larger, this ability to change diminishes very quickly.

Initially, to test fiber performance in the active regime a single stage fiber amplifier based on 3 m of LCF1 was constructed. The amplifier fiber ends were angle cleaved to $\sim$ 8 degrees. This amplifier was seeded by a micro-chip laser operating at 1064 nm with 125 mW (5 μJ) output at 25 kHz repetition rate and was counter-directionally pumped. The measured pulse duration of the micro-chip laser was 600 ps. The amplifier performance is summarized in Fig. 6. The measured amplification slope efficiency is $\sim$ 57%. A maximum power of 7 W (320 μJ) was obtained before the onset of lasing at the amplifier gain peak of $\sim$ 1026 nm. The measured M^2 at 7 W output power was $M_{\rm x} = 1.17$ and $M_{\rm y} = 1.18$ for the two orthogonal orientations, respectively (see inset in Fig. 6). Output mode pattern is insensitive to the launch condition. The possibility to handle high peak powers with LCF1 fiber was tested using a two stage fiber amplifier configuration. At the amplifiers output 15 W (600 μJ, $\sim$ 1 MW) were obtained, limited by available pump power. No obvious signatures of self-phase modulation and Raman scattering were observed (see inset in Fig. 6 for experimentally measured spectrum at 400 μJ). The amplified spontaneous emission level was over 40 dB below amplified signal level in the output spectrum.

IV. Conclusions

We have demonstrated theoretically and experimentally that LCFs can extend effective fundamental mode areas in an essentially single mode fiber by over two orders of magnitudes over that of a conventional single mode fiber. This substantial increase of effective fundamental mode area in optical fiber lasers and amplifiers will usher in a new era of high power ultrafast laser science and technology. At the same time a wide range of industrial applications in material processing and micro-machining will greatly benefit from the dramatically improved modal properties and increased power capabilities of future industrial LCFs operating in the anticrossing regime.

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Brian K. Thomas, photograph and biography not available at the time of publication.

Martin E. Fermann, photograph and biography not available at the time of publication.