LLNL-TR-603293

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# Science and Technology of Unconventional Fiber Waveguides for Emerging DoD and DOE Laser Missions: Final Report

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**November 26, 2012**

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Science and Technology of Unconventional Fiber Waveguides for Emerging DoD and DOE Laser Missions: Final Report

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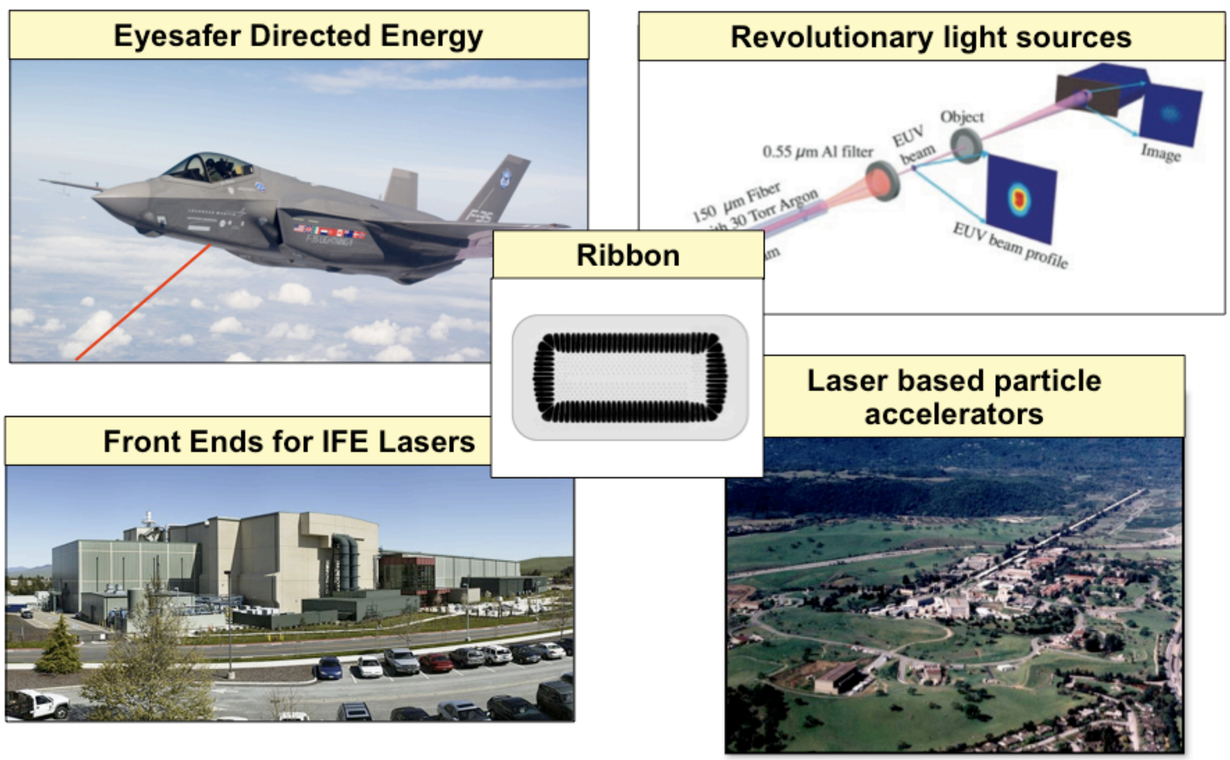


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*Executive Summary*

Lasers, in general, convert electricity to highly directional photons. Fiber lasers are especially appealing because they make this conversion relatively efficiently; wall-plug efficiencies on the order of 30% are available today, and efficiencies as high as 40% are possible. For the types of fiber lasers that are being built for heavy manufacturing tasks, this efficiency is a key advantage, though other attributes add to their appeal, including maintenance free lifetimes greater than 10,000 hours and the ability to operate at a wide range of wavelengths spanning 900 nm to more than 2,000 nm. Last year, commercial sales of fiber lasers for cutting and welding exceeded $200M[i], making them the fastest growing segment of the laser market.

Fiber lasers are also being developed for the applications that interest DoD and DOE. Most of these call for high-quality beams; that is, for the divergence of the laser's beam to be diffraction-limited. Fiber lasers can excel in this regard; while industrial-grade fiber lasers tend to produce spots having diameters of a few 10's of microns at a distance of one meter (adequate for their needs), diffraction-limited or "single-mode" fiber lasers can produce comparably-sized spots at a distance of one kilometer (given a reasonably sized focusing optic). The fiber lasers considered here are all diffraction-limited and outside the development path of industrial systems.

It is clear that highly efficient, diffraction-limited fiber lasers with megawatt-class powers or joule-class pulse energies will enable a host of new missions for DoD and DOE, including the generation of mono-energetic gamma rays, directed energy weapons, range finders and remote sensors, laser-based particle accelerators, K-alpha X-ray sources, extreme ultraviolet sources and lasers for advanced materials processing. Further, the waveguides developed under this proposed initiative may also be employed for high power and high-energy light transport. Diffraction-limited, fiber lasers are currently limited, though, to powers of 10 kW and pulse energies of a few mJ, falling short of the DoD and DOE needs by one to two orders of magnitude. Extensive studies by LLNL have shown that the root of these limits lies in the fibers' circular symmetry, and intriguingly, that these limits can be increased by two orders of magnitude by switching to a ribbon-like waveguide geometry.

The key to scaling to higher powers and pulse energies, then, is to solve the technical challenges associated with fabricating a ribbon-like fiber. The research was broken into three key goals. First, new fabrication techniques were developed to make ribbon fibers available for use and testing. Second, mode conversion techniques were modeled, fabricated and tested. Third, a laser system demonstrating all the critical physics for a ribbon fiber capable of scaling beyond 30kW was constructed and tested.

Early progress was made in mode conversion resulting in the publication of one paper in Applied Optics[1] and a second that has been accepted for publication in Optics Express[2]. Progress on the first and third goals has been significant and publications relating to these are

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[1] A.L. Bullington, et al., "Mode conversion in rectangular-core optical fibers," Applied Optics, vol. 51, pp. 84-88 (2012)

[2] A.K. Sridharan, et al., "Mode-converters for rectangular-core fiber amplifiers to achieve diffraction-limited power scaling," accepted for publication in Optics Express.

being developed.  This technical report summarizes that progress.  The results contained here are being prepared for publication as 2-3 separate papers that will be submitted to peer reviewed journals in the near future.

## Fabrication of Photonic Crystal Ribbon Fibers

Here we describe the fabrication steps leading to the world's first rare-earth doped photonic crystal fiber.  Due to the high cost of telecom-grade rare-earth doped glass, we broke the fabrication development into pieces, using relatively inexpensive glass while developing the fabrication steps for air-clad circular-core fibers, air-clad ribbon-core fibers, and double-clad fibers.  With these pieces mastered, we moved on to the final Yb-doped fiber.  We are happy to report that, thanks to our preparations, we completed this fiber on our first attempt.

The fabrication effort, conducted during FY2012, is the culmination of several years of modeling and facilities preparations.  The effort was highly successful; the resulting fiber met fully our requirements and expectations; its laser performance is the topic of a second report which will also be submitted to a peer-reviewed journal.

*Facility*

Figure 1 shows the key pieces of LLNL's new photonic crystal fabrication facility, purchased and installed in FY2010 and FY2011 with licensing and royalty funds (funds that fell outside this initiative, though the facility is central to this work).  The key pieces are an 8.2 meter draw tower comprising a furnace that can reach temperatures of 2100 C; a mechanism for pulling capillaries and canes (roughly 1 to 3mm diameter); a mechanism for pulling fibers (roughly 100 to 500µm diameter); and a computer to control the furnace and pulling mechanisms.  The facility also has a glass-working lathe with a hydrogen-oxygen torch and a jig for stacking capillaries and canes into photonic crystal preforms (the preforms are drawn into fibers in a subsequent step).

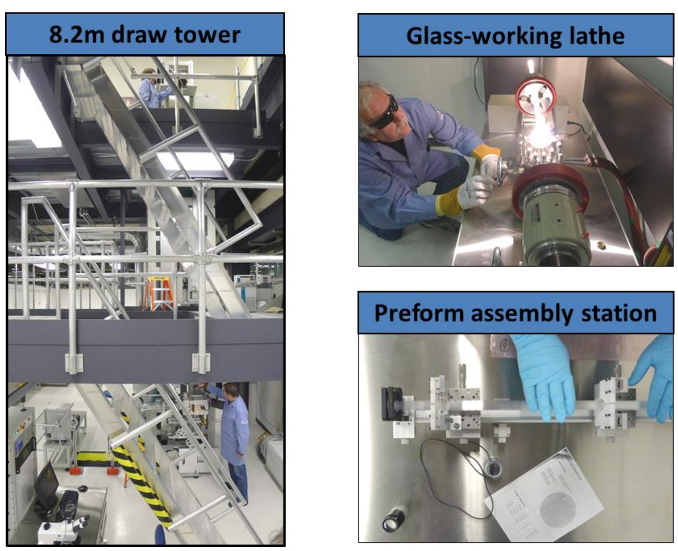
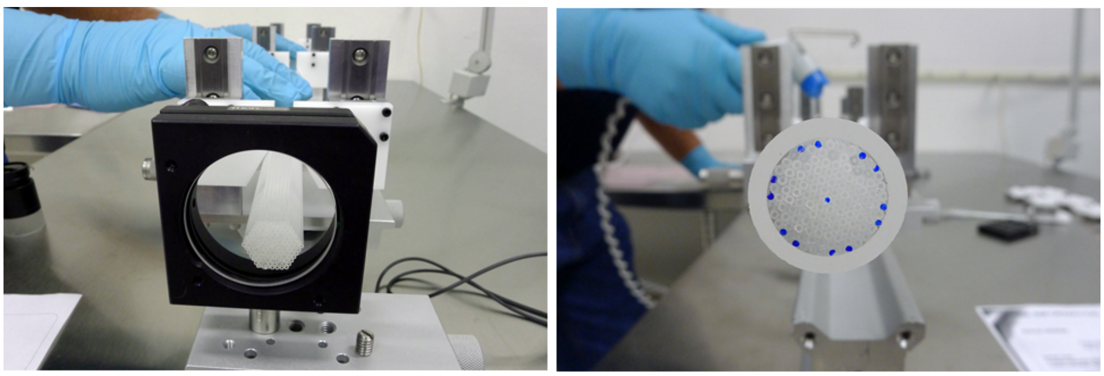



**Figure 1** Optical fiber draw tower and associated equipment for fabricating photonic crystal fibers, a facility recently completed at LLNL.

### *General fiber fabrication*

Fiber fabrication is new to LLNL and ribbon-core fibers are new to the world; understandably, the fabrication team met – and overcome – many challenges.

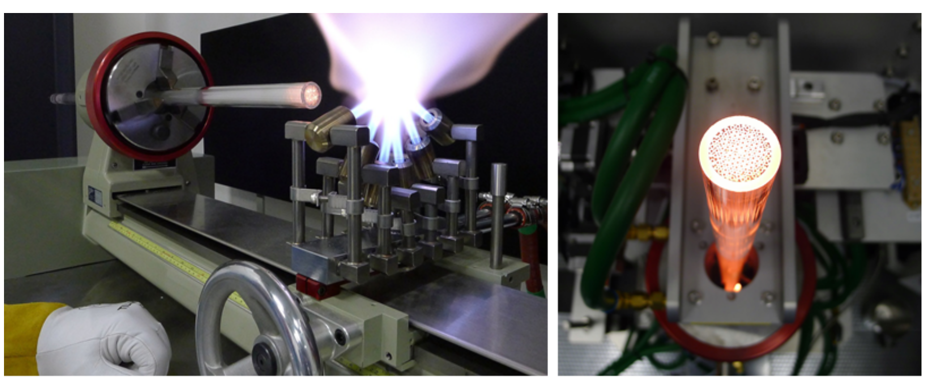
The initial work involved mastering the photonic crystal fabrication technique, whose first step is to draw commercial silica rods and tubes – rods roughly 25mm in diameter and the tubes ranging from 11×25mm (inner × outer diameter) to 30×36mm – into canes and capillaries with outer diameters of typically 1.500mm, typically controlled to within ± 3µm.  The next steps are to stack these into a photonic array (Figure 2) and to insert the array into a tube to make the photonic preform (the precursor to the photonic fiber).



(a) (b)

**Figure 2** (a) Canes and capillaries stacked into a hexagonal photonic array and (b) the array modified (corner pieces removed) and inserted into a preform tube.  The rods in (b) have been marked blue so they stand out; the central blue rod will be the light-guiding core of the final fiber.

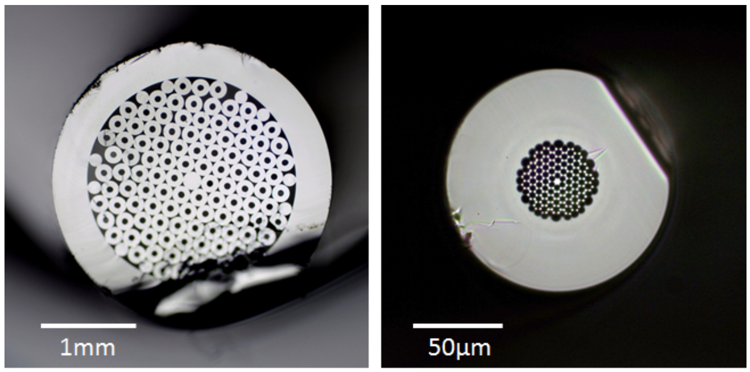
The ends of the preform are then fused on the glass-working lathe to fix the canes and capillaries in place – that is, to prevent them from falling out when the preform is held vertically in the furnace (Figure 3).



(a) (b)

**Figure 3** (a) After the canes and capillaries have been stuffed into the preform tube, their ends are sealed (melted slightly) so they cannot fall out of place when the rod is held vertically in the draw tower.  (b) Looking down onto the preform as it is mounted into the tower.  The preform glows because it guides the blackbody radiation from the 2000 C furnace (centered at a wavelength of roughly 1.5µm, but with a large component in the visible portion of the spectrum).

The final step is either to draw the preform directly into fiber, or to draw it into a photonic cane (typically 3mm in diameter) that is subsequently sleeved in yet another glass tube before being drawn into fiber. Figure 4 shows a photonic cane and its resulting fiber.




(a) (b)

**Figure 4** Microscope photographs of (a) a photonic cane and (b) an optical fiber drawn from that cane. While drawing the fiber in (b), a vacuum port sucks air from between capillaries while a pressure port forces a relatively small amount of air into the capillaries (in this case, the pressure was set to 4kPa).

### *Ribbon fiber fabrication*

The ribbon fiber adds three fabrication challenges: creating a ribbon-like core; creating a cladding to guide pump light inside the fiber (the end goal, of course, is for the fiber to form a laser); and incorporating rare-earth doped glass into the core, an expensive undertaking.

Though creating a ribbon core is relatively straightforward, we chose to practice with stock silica glass ($1,500) before committing the rare-earth doped glass ($40,000) required for the final fiber. Figure 5 shows the results of several attempts and illustrates the importance of fine pressure control; the difference between the holes being barely opened and being an ideal size – Figures 5a and 5b – is just 0.5kPa, or 0.07 psi.

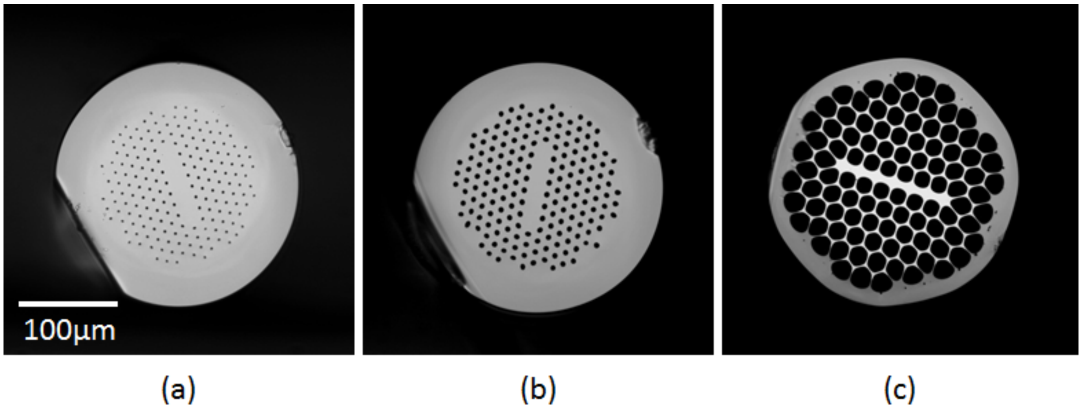



**Figure 5** Microscope pictures of several air-guided ribbon-core fibers; the scale is the same for all photos. The pressure applied to the capillaries varies from 2kPa for (a) to 2.5kPa for (b) to 4kPa for (c). (a) and (b) were drawn from the same preform; (c) is from a preform having a slightly different design.

Creating the air-cladding turned out to be one of our bigger challenges; Figure 6 shows the results our best attempt. There are really two challenges: creating a large number of air holes around the circumference of the cladding (a preform fabrication challenge) and making the veins between holes as thin as possible (a fiber fabrication challenge, because if the holes are puffed out too much – making the veins more desirably thin – they tend to pop easily).

Figure 6 shows the results our best result; here, we found that a 0.3kPa pressure change (0.04psi) was the difference between adequate holes and holes that popped.

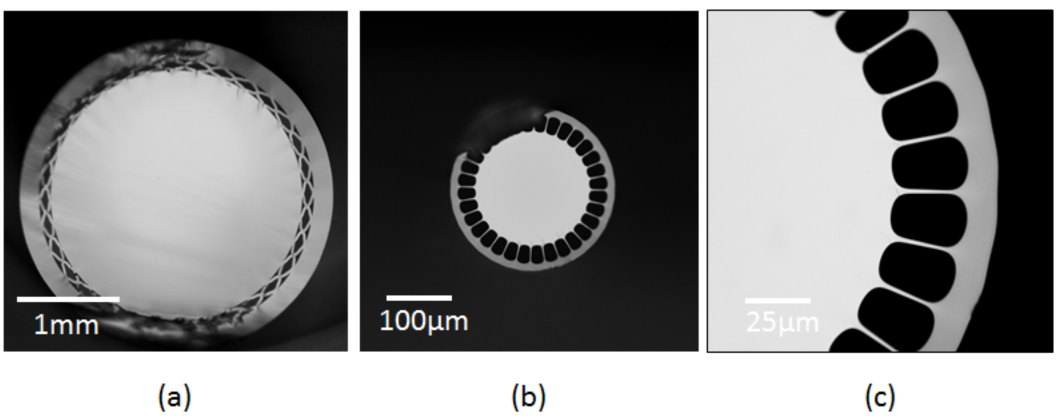



**Figure 6** An air-clad fiber; note that for this practice attempt, the central region of the fiber does not have a guiding structure. (a) shows a cross-section of the photonic cane and (b) and (c) show fiber drawn from that cane. (c) is from the same section of fiber as (b), but viewed with a higher magnification. The numerical aperture of the fiber depends on both the thickness of the veins between the holes (thinner veins yield a higher numerical aperture) and on the number of holes around the circumference (the more holes the higher the numerical aperture). This fiber achieved a numerical aperture of 0.4, our best result.

### *Rare-earth doped ribbon fiber*

Having completed the test runs of the air-guiding ribbon core and the air-cladding, the ribbon fiber was straightforward; the trial runs were essential, of course, because of the cost and scarcity of the rare-earth doped core rods.

We placed the order for the Yb-doped core rods from Heraeus Tenevo in November of 2011 and received them in July of 2012. Each of the 15 1m rods had a diameter of 1.25mm, a refractive index of +0.00253 relative to silica, and doping concentrations of 0.05 mol% $Yb_2O_3$ and 1.0 mol% $Al_2O_3$; all metrics met our specifications. The doped-glass's raised refractive index created a core having a numerical aperture of 0.085; by keeping the narrow-dimension of the ribbon core less than 8μm we kept the fiber single-moded along that axis.

Figure 7 shows the final photonic cane and ribbon fiber, combining for the first time a ribbon core with an air cladding. The fiber met all of our performance targets; it optical performance is discussed below.

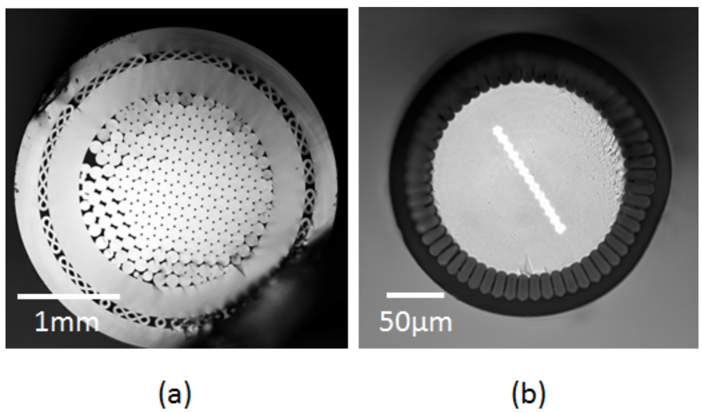



**Figure 7** (a) A photonic cane having an air-cladding and inner guiding structure, and (b) the final rare-earth doped ribbon fiber. On (b) the central ribbon core has a higher refractive index than its surroundings, and thus preferentially guides light (as intended).

## Testing of LLNL Ribbon Fiber Samples

High average power fiber lasers from 10s of kW to greater than 100 kW are of interest to manufacturers and the defense industry. Theoretical limits on diffraction limited circular geometry fiber lasers limit the average power to 2 kW for narrowband and 10-36 kW for Broadband lasers [1]. We have proposed an alternative ribbon fiber geometry to allow scaling of fiber lasers far above these limits in which a single high order ribbon mode with a high effective area is amplified to be converted back to the fundamental mode once in free space [2–5]. This ribbon fiber geometry offers increased effective area to mitigate nonlinear effects, and improved thermal properties. Here we report the first air-clad, Ytterbium doped ribbon fiber and it is operated in three different configurations, a single high order mode amplifier, and as an oscillator both in single mode and multimode regimes. The amplifier was operated in a single high order ribbon mode with a scalable area of approximately 600 $\mu m^2$. The amplifier shows 50% slope efficiency, and achieves 24 dB of gain at 10.5 W limited by seed power. In an alternate configuration, the active ribbon fiber is also operated as a multimode oscillator showing 71% slope efficiency at 40 W of output power. Also, in initial, low power, experiments, we demonstrate single mode oscillation with 44% slope efficiency, and 5 W of output power.

# High purity illumination of high order ribbon fiber modes

## Mode conversion of high order ribbon fiber modes

Index guided, rectangular core ribbon fibers are necessarily multimode in the wide dimension. Figure 8 shows a PCF ribbon fiber fabricated via stack and draw at Lawrence Livermore National Lab (LLNL). The modes of a ribbon core are similar to those of a slab waveguide. Each mode is formed of a series of intensity peaks, which alternate in phase from 0 to π. Figure  illustrates the near field of a four lobed mode of the PCF ribbon fiber. The far field of a ribbon fiber mode has two primary lobes and a series of smaller lobes between them for any mode greater than the fundamental. Figure  illustrates the far field of the previously discussed four lobed mode.

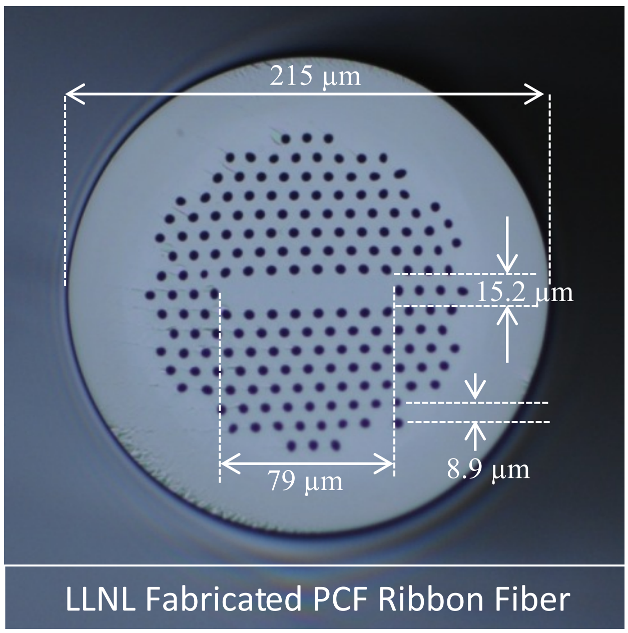



**Figure 8: Photonic crystal ribbon fiber with a rectangular core cross-section**

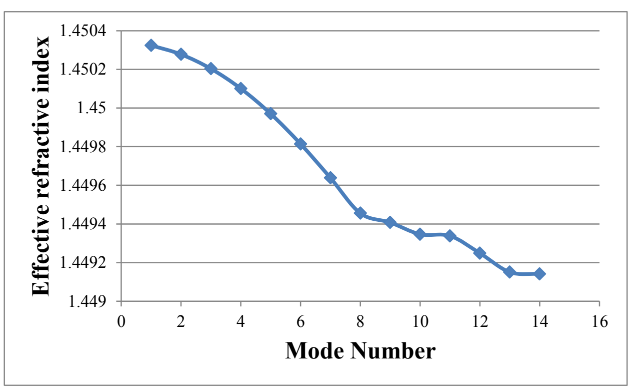



Figure 11 shows the effective index as a function of mode number in a ribbon fiber with an approximately 80 µm width and a 15.2 µm height. The closer the modes are in effective index the more difficult it is to illuminate only one, and the more likely that once illuminated the power will leak into nearby modes. A high order mode, once illuminated, has high separation between its nearest neighbor modes, and, as we have demonstrated, can be converted back into the fundamental mode in free space with high efficiency [4,5]. It is clear that if the fiber bend radius is small in the wide dimension, the power in the high order mode may still leak into nearby modes despite greater separation in effective index. For this reason, ribbon fibers are designed to be bent in only the narrow single mode dimension. This allows the wide dimension of the fiber to be arbitrarily increased to increase power, while not sacrificing the compactness associated with fiber lasers.

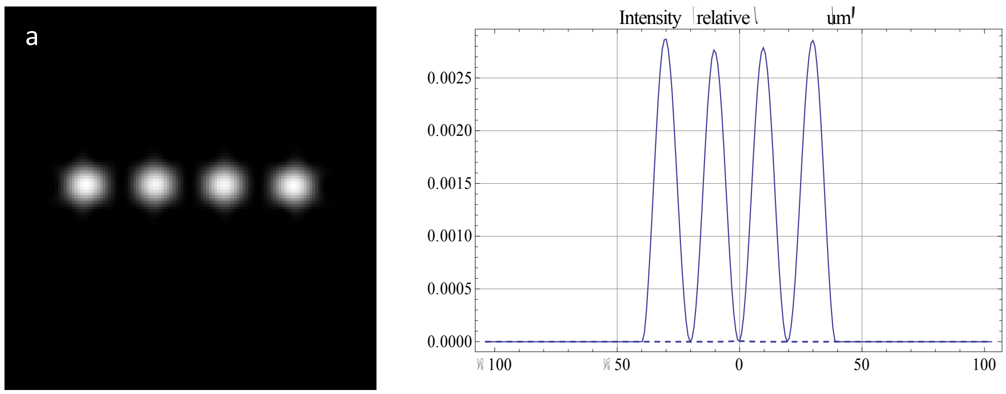



Figure 9: Near field intensity plot for a four lobed ribbon fiber mode, (a) 2D linear intensity plot, and (b) 1D linear intensity plot

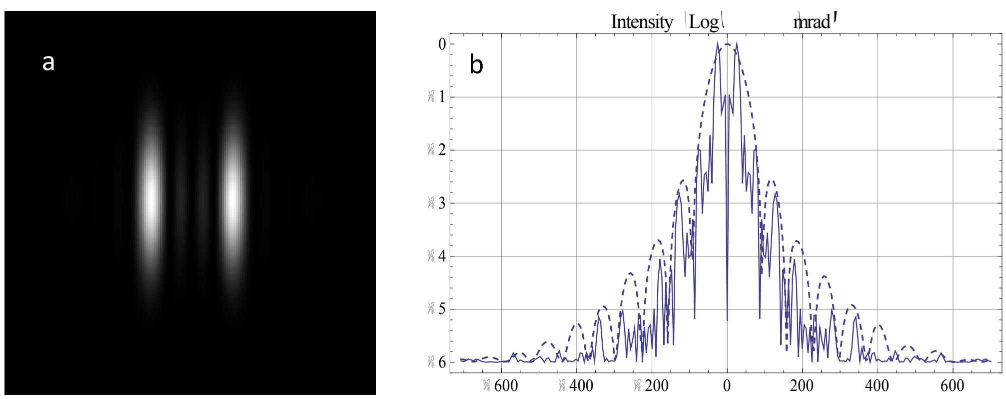



Figure 10: Far field intensity plot for a four lobed ribbon fiber mode, (a) 2D linear plot, and (b) 1D logarithmic intensity plot, 6 decades.

A prerequisite to successfully amplify a single high order mode in a ribbon fiber is a high purity illumination of a particular mode. Figure , discussed above, shows the near field of a typical high order mode in a ribbon fiber. It is worth noting here that each near field lobe has a phase alternating between 0 and π. We have previously demonstrated a method to convert from a fundamental Gaussian beam in free space to a multi-lobed ribbon mode with alternating phase with high efficiency by use of a pair of spatial light modulators [5]. Spatial light modulators, although possible to make for use at high power, are typically only suitable for use with a few milliwatts of power. This mode conversion approach can be used to generate static phase plates to accomplish the same mode transform demonstrated in [5] for use at higher power.

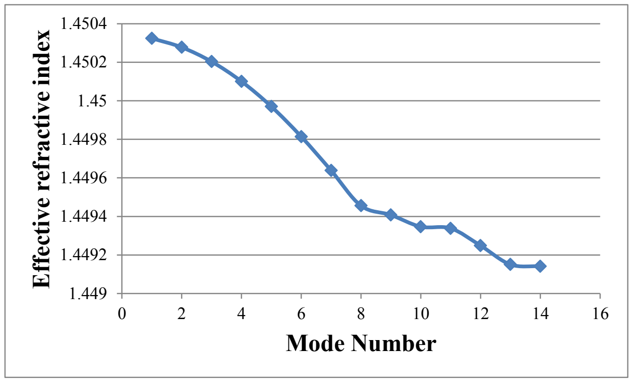



**Figure 11: Effective refractive index v.s. mode number for a ribbon fiber. Modes 10 and above are lossy modes, while the lower modes have low index separation between neighboring modes. Middle modes are confined more than higher modes and have improved isolation over lower modes.**

However, in the case that spatial light modulators are unavailable at the desired power level, and custom transform plates are also not available, a conversion to a high purity mode can be made by the use of a simple phase plate with alternating 0 to π phase, and a cylindrical lens. In this approach, the conversion efficiency suffers in comparison to the SLM approach, but the purity of the illuminated mode can be as high as 99%.

## High order mode illumination experimental setup and procedure for alignment

The experimental setup for illuminating a high order ribbon fiber mode using a simple phase plate is shown in Figure . First a collimated fundamental mode Gaussian beam in free space is focused by a cylindrical lens into a cylindrical beam oriented with the wide dimension parallel to the optical table. At the focal plane of the narrow dimension a binary phase plate is placed in the beam path. The phase plate should have at least as many half periods of 0 to π phase shift as lobes in the desired ribbon mode with a full period equal to the spacing between two lobes of the desired mode. Recall that the lobes of an ideal high order ribbon mode are of equal peak intensity. In order to properly illuminate this mode, it is necessary to illuminate the correct number of periods on the phase plate with a nearly flat top beam. The simple way to accomplish is to illuminate the phase plate with a beam three times wider than the width of the desired number of phase periods, and clip off the power outside the central region with a one dimensional spatial filter.

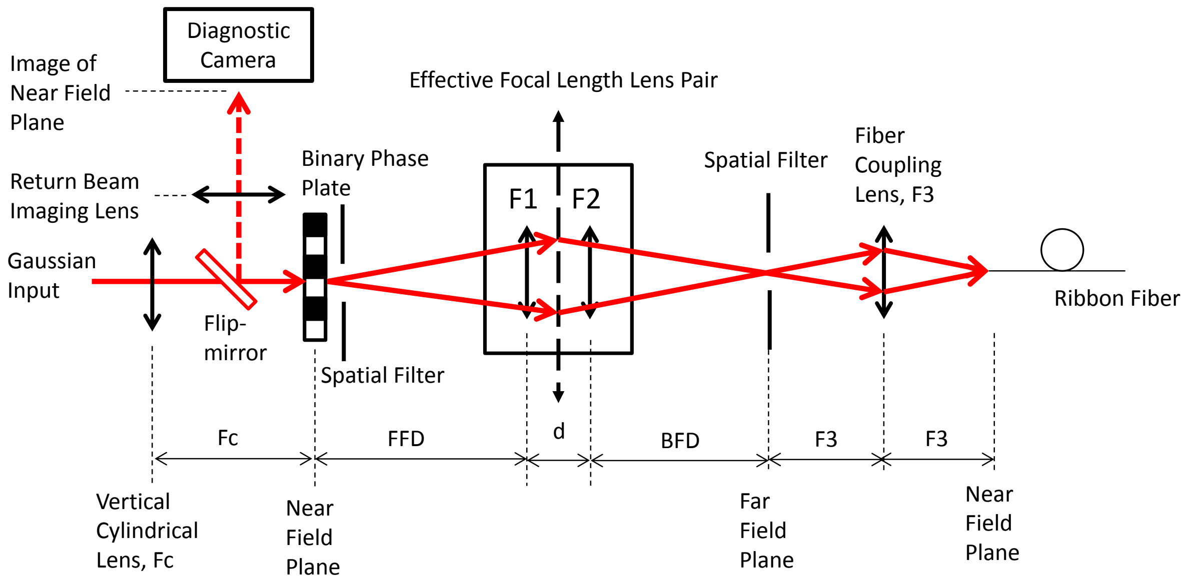



**Figure 12: Single high order ribbon fiber mode illumination experimental setup. FFD = front focal distance, d = distance between effective focal length lens pair, BFD = back focal distance.**

The mode exiting the phase plate-spatial filter portion of the setup is a nearly flat top beam with a series of 0 to π phase shift across. The far field intensity pattern of this beam has two primary lobes, much like the far field of a ribbon fiber mode, but also has a series of wider angle lobes of diminishing intensity. These additional lobes are not surprisingly a result of the Fourier spectrum of a square wave phase applied to a flat top intensity profile. In order to better mode match with the far field of the desired high order ribbon mode, these additional higher angle lobes are also clipped. The effect is that the near field intensity pattern now shows a series of lobes with presumably alternating 0 to π phase shift between them, and the far field is limited to the two primary lobes symmetric about the center. This near field and far field pair is now a magnified approximation of a high order ribbon mode.

The final step in successfully launching the mode into the ribbon fiber is de-magnifying the near field beam, phase and intensity, such that it precisely matches the near field of that mode at the fiber face. A simple imaging system which de-magnifies the intensity but not the phase will not due, as both must match to obtain a high purity mode. An adjustable magnification four-f transform system is necessary. In our setup, the fiber coupling lens is an aspheric lens with a fixed focal length. The effective focal length lens pair however can be adjusted until the correct magnification is reached. The equation to determine the effective focal length of a lens pair is given in Equation (1). While knowing the effective focal length of a particular lens combination, this focal length is the distance from the principle plane to the focal plane of the lens system. The physical distances from the front focal plane to the first lens, and the second lens to the back focal plane are given by the front focal distance, Equation (2), and the back focal distance, equation (3), respectively. All these distances are illustrated in Figure 12. The equations for the front and back focal distances assume the thin lens approximation for each of the two lenses in the effective focal length lens pair.

$$f' = -f = EFL = \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{n * f_1 * f_2}\right)^{-1} \quad (1)$$

$$FFD = f + P_1 \quad (2)$$

$$BFD = f' + P_2 \quad (3)$$

$n$ is the refractive index of the medium between the lens pair, in this case air, $d$ is the distance between the two lenses, and $f_1$ and $f_2$ are the focal lengths of lens 1 and lens 2 respectively. $P_1$and $P_2$ are the distances form lens 1 and lens 2 to the front and back principle planes and are given by:

$$P_1 = n\frac{f}{f_2}\frac{d}{n}$$

$$P_2 = -n\frac{f}{f_1}\frac{d}{n}$$

The locations of the principle planes are not illustrated in the experimental setup, as they will move significantly depending on the particular lens combination that is chosen.

An initial guess for the correct magnification can be made by comparing the ribbon core width to the product of the half period of the phase plate and the number of lobes in the desired mode. Once the magnification is determined, then an effective focal length for the lens pair can be calculated by multiplying the fiber coupling lens focal length to the magnification. Next, a pair of lenses should be selected such that when placed a certain distance apart, the desired effective focal length is achieved according to Equation (1). It is important when doing this last step to check the front and back focal distances to make sure the front focal distance of the lens pair is (-) and the back focal distance is (+). Otherwise, it will be impossible to place the phase plate in the front focal plane of the lens pair and/or to match the focal planes of the fiber coupling lens and the back focal plane of the lens pair.

With the lens system, comprised of the fiber coupling lens and the effective focal length lens pair, in place, the final fine tuning of the magnification can be performed. A reverse propagating magnification diagnostic beam path must be put in place with a removable flip-mirror mirror such that the image of the phase plate is incident on a camera. The transitions between phases should be visible distortions on the camera when it is in focus. Matching these phase transition features to the desired mode will allow a fine tuning of the alignment.

A beam near the wavelength of interest should be launched into the fiber in the backward propagating direction such that the fiber on the mode launch side is illuminated by reverse propagating light and imaged onto the phase plate and therefore also onto the diagnostic camera. The light arriving on the camera will be multimode, but the lobe locations of a single high order mode are known with respect to the full width of the fiber core, and should line up with the phase transitions of the phase plate. These phase transitions are not perfect, and can therefore be seen on the image plane along with the image of the fiber end face illuminated by backward propagating light. With the image of the fiber end facet and the phase plate incident on the same camera, the effective focal length lens pair can be adjusted to a slightly longer or shorter focal length until the fiber core lines up with the transitions of phase in the near field image plane. Figure 13 shows an image of a photonic crystal ribbon fiber with a rectangular guiding core region with an illustration of the phase plate features and modal features of interest overlaid on the image. Care should be taken when adjusting the effective focal length of the lens pair to also adjust the front and back focal distances.

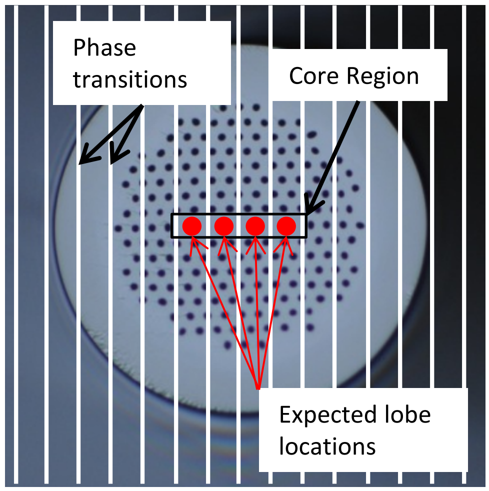



Figure 13: Illustration of a magnification diagnostic image, with illustrated binary phase plate transitions and expected mode profile overlaid on an image of a photonic crystal ribbon fiber with a rectangular cross-section core.

All that remains to complete the alignment is to make sure the fiber tip and tilt angles are aligned to the incoming mode. The vertical tip angle can be aligned easily by maximizing coupled power in the forward direction. The horizontal tilt in the fiber's wide dimension however requires an additional alignment step. In order to determine modal content, a diagnostic image of the near and far field of the output should be put in place during this final step. With the removable flip-mirror removed, the reverse propagating beam also removed, and the forward propagating beam resumed, the tilt of the fiber should be adjusted until only two peaks are visible in the far field of the fiber output, and the desired number of lobes is visible in the near field. It is often difficult to tilt a fiber without also adjusting its horizontal translation. If the horizontal translation is displaced from the original alignment, the reverse propagating diagnostic can be used to re-align it.

Following the steps detailed in this section, a single high order mode can be illuminated with 90% purity by an initially Gaussian beam, allowing high gain amplification of the coupled light. The efficiency of the above detailed mode transform setup is around 10 %, which is not desirable in any final system, but as demonstrated in [5], a custom multiple phase plate solution can make the transition with high efficiency if such phase plates are made. The purity of the illuminated high order ribbon mode, can theoretically be as high as 99% and is demonstrated in this report to be 90%.

## Passive photonic crystal ribbon fibers and high order mode illumination results

Here we report a passive photonic crystal ribbon fiber and illumination of a single higher order mode with 90% purity and a mode area of 650 μm$^2$. Figure 8 shows an image of the end face of the ribbon fiber. In a high power ribbon fiber, the outer cladding would also be rectangular to allow selective bending and better thermal control, but the initial fibers described in this report all have round outer claddings.

Using the method described in the above section, a high order five-lobed mode was illuminated with 90% purity. The near and far fields, of the expected mode, and of the measured mode are shown in Figure (a) and (b) respectively. These passive ribbon fibers, have no doping, but can be used for high intensity transport of high average or high peak power lasers with mode converters on either end. Guiding is achieved by a set of air holes that lower the average index of the region around the core. This fiber has 14 modes. A middle mode was chosen because low order modes have lower modal isolation from higher order modes as discussed in the introduction, and the highest order modes can be lossy. In this case, a middle order mode is a good balance between modal isolation and high confinement.

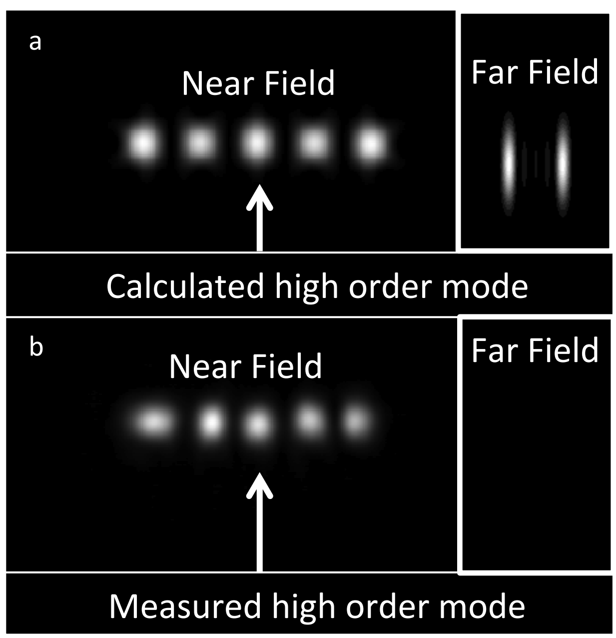



**Figure 14: The near and far field profiles of a single five lobed mode of the photonic crystal ribbon fiber of Figure , calculated (a), and measured (b)**

An ideal active ribbon fiber will be a PCF ribbon fiber like the passive fiber of Figure , but have active doped rods whose index is matched to the surrounding glass. These rods would spatially overlap with the lobes of a particular desired mode providing mode selective gain. Such an ideal active ribbon fiber would have excellent mode selectivity and could be used as an oscillator or an amplifier with inherent modal purity. A previous ribbon fiber demonstration here at LLNL has demonstrated an active ribbon fiber in which the active rods apply selective gain to a desired mode, but had slight variations in index uniformity across the core and used [2,3].

## Active ribbon fibers and high order mode illumination results

Reported here is the first air clad ytterbium doped ribbon fiber with a fully doped core region shown in Figure . The method discussed above for high order ribbon fiber mode illumination with a simple binary phase plate was used to illuminate a single high order mode of the fiber. Figure shows the near and far field profiles of the mode through the active fiber with a mode area of approximately 600 $\mu m^2$. Larger mode area fibers are possible as the core height can be increased up to the single mode limit which depends on the fiber NA, and the core width up to the limit of fabrication capabilities. Although a major undertaking, it is not unreasonable to make a fiber with a 500 µm core width which would increase the mode area over this result by nearly five times. This fiber was fabricated via a stack and draw technique similar to the above passive PCF fiber, but without any air holes near the core region. In this case, core guiding was achieved by the raised index of the ytterbium rods. The far field mode of this fiber appears much like a standard ribbon fiber mode in that the power is mostly confined to a pair of lobs symmetric about the center indicating the existence of a pure mode. The near field of this mode, despite the discrete lobe locations, has an unusual envelope across the mode with each lobe displaying variations in intensity. We believe this is due to variations in the ytterbium rod doping concentrations and index. A separate multiple core ytterbium ribbon fiber effort demonstrated similar behavior of the individual power content in each particular near field lobe [6].

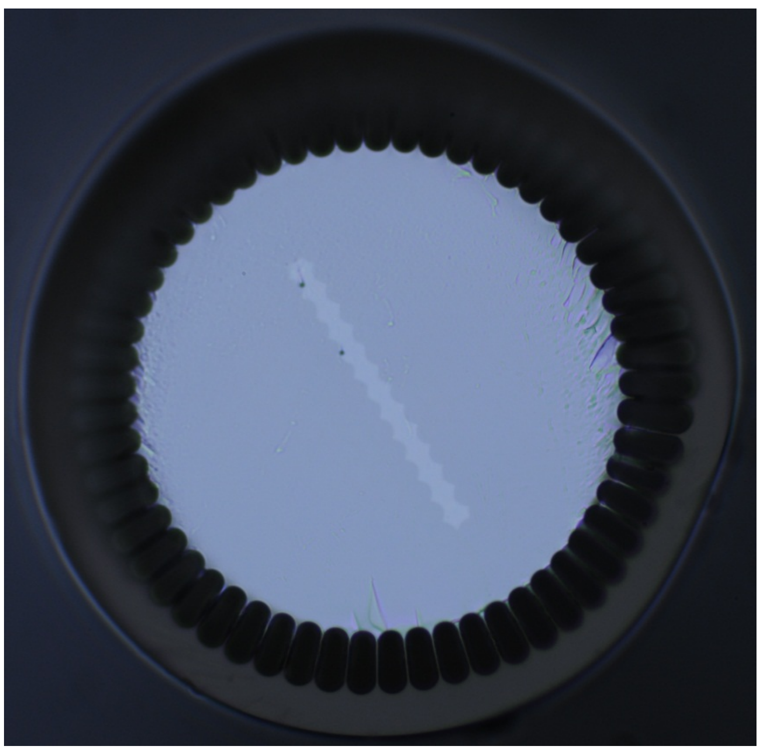


**Figure 15: Air clad, Ytterbium Doped Ribbon Fiber**

As discussed in the previous section, ideally, ytterbium rods with uniform refractive indexes carefully matched to the surrounding glass would be obtained such that guiding in the core region would be achieved not by the raised index of the core rods, but instead via photonic crystal air holes as demonstrated in the above passive fiber of Figure and modes of Figure . However, the far field is a good indicator of single mode operation, and as will be seen in the following section can be amplified to high gain without adding significant modal impurities.

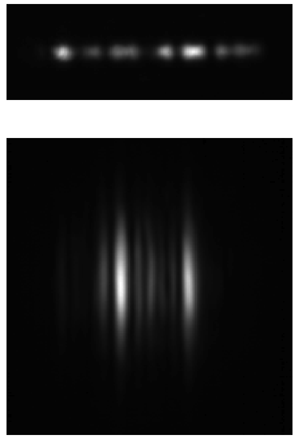


Figure 16: The near field (top), and far field (bottom) of the high order mode illuminated in the Ytterbium doped ribbon fiber at low power

## Ytterbium doped, air clad, single high order mode ribbon fiber amplifier results

The experimental setup for the single high order mode ribbon fiber amplifier is shown in Figure . The output of the previously described high order mode launch setup is coupled into the ytterbium doped ribbon fiber shown above in Figure . The pump is launched into the amplifier output end in a counter-propagating configuration, while the signal output is measured for power and the images of the near field and far field intensity are collected. The power and mode profile data was taken after passing through a band pass filter around the signal wavelength to eliminate any ASE that would otherwise be polluting the measurements, but the spectral data was taken unfiltered.

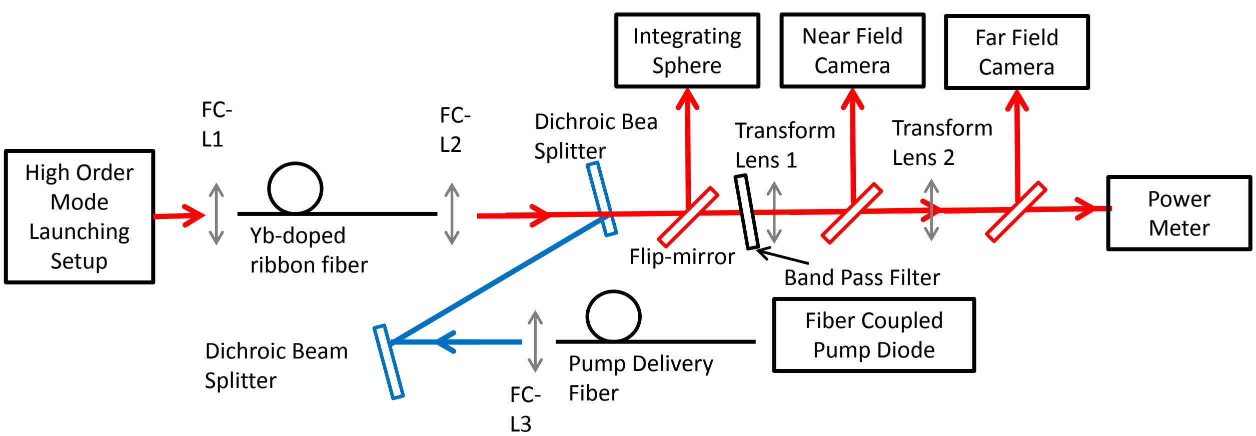



Figure 17: Ytterbium doped ribbon fiber amplifier experimental setup

Figure  (left) shows the signal output power v.s. coupled pump power, and Figure  (right) shows signal gain v.s. coupled pump power. The amplifier reached a gain of 24 dB, at a power of 10.5 W. The slope efficiency of 50 % is lower than is possible, as only 38 mW of seed power can be coupled into the fiber with the available seed laser. In this case a significant amount of power is being converted to ASE rather than going into amplified signal as the spectrum suggests. Alternate methods of mode launching into a single ribbon mode, such as the double phase plate approach of reference [5], or a ribbon fiber oscillator seed operating in the desired mode, would improve the efficiency. Figure 1 shows the spectrum of the amplifier output at the highest gain measurement.

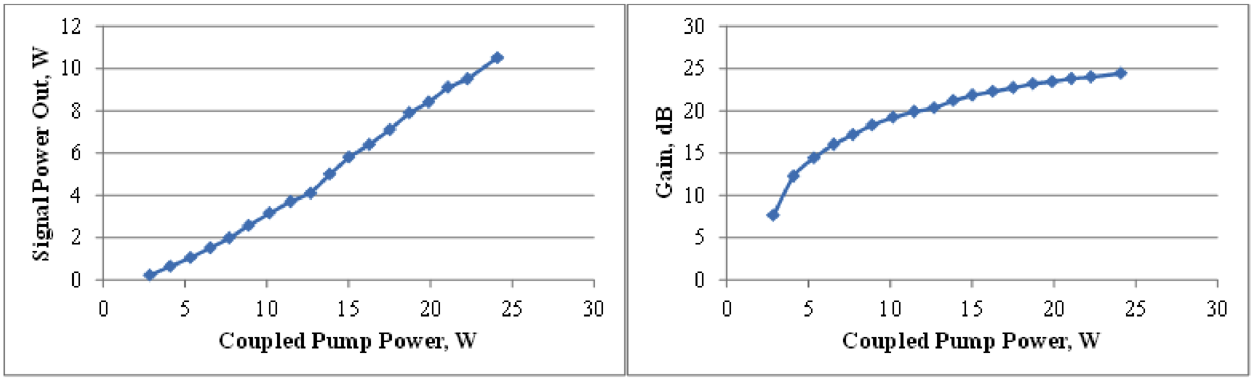



Figure 18: Signal power out (left) and gain (right) v.s. coupled pump power

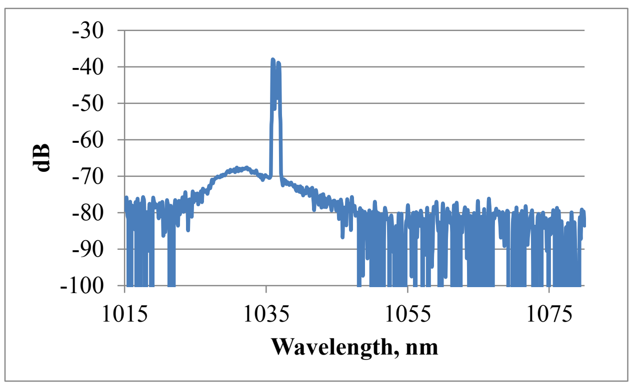



Figure 1: Spectrum of the ribbon fiber amplifier at the highest measured power level of 10.5 W.

The modal purity as evidenced by the far field profile remains unchanged through most of the amplification curve, although impurities that began as insignificant grow as saturation is approached. Figure  shows the near field and far field profiles of the output field at various gain values. The near field manifests as a superposition of the intended mode and any impurities present, while each far field mode is spatially isolated, and the growth of the impurities can be clearly observed. Note that 20 dB of gain is achieved without any significant change in the mode.

This result shows that a single high order ribbon fiber mode can be launched into an amplifier, and the mode can be amplified to high gain levels even in the absence of mode selective gain with modal degradation only occurring for the highest gain values. However, it also underscores the value of incorporating both, carefully index-matched core rods, and mode selective positioning of the gain elements; the former to achieve high quality modes such as in the above photonic crystal ribbon result of Figure , and the latter to achieve improved single mode amplification such as was proposed in references [2,3].

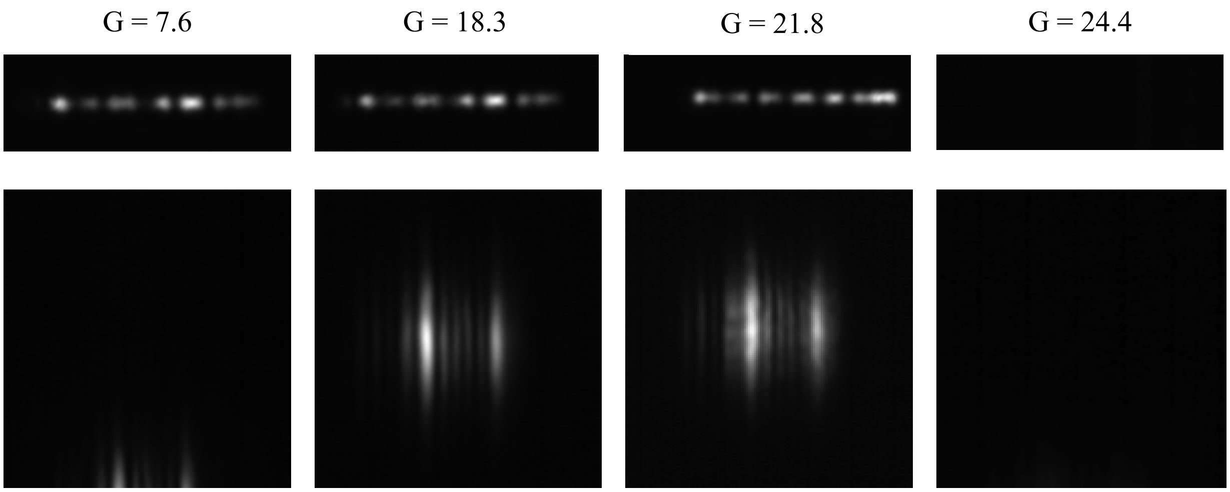



Figure 20: Near field (top row) and far field (bottom row) images of the signal output at four different gain values.

# Ytterbium doped air clad ribbon fiber oscillator

## Multimode ribbon fiber oscillator

In the previous sections, the process of launching into a single ribbon fiber mode and amplifying that mode to high gain was described in detail. In this section, a different approach is used in which the fiber is operated as an oscillator rather than an amplifier. Here we will first describe the properties of the ribbon fiber oscillator with unfiltered multimode operation, and will discuss single mode selection and oscillation in the next section. By flat cleaving one end of the fiber and providing a Fourier transform reflection on the other, the fiber becomes a ribbon fiber multimode oscillator. Figure shows the experimental setup with the optional mode selection filters which will be discussed later. Figure shows the output laser power v.s. coupled pump power giving a slope efficiency of 71%, and a maximum output power of greater than 40 W.

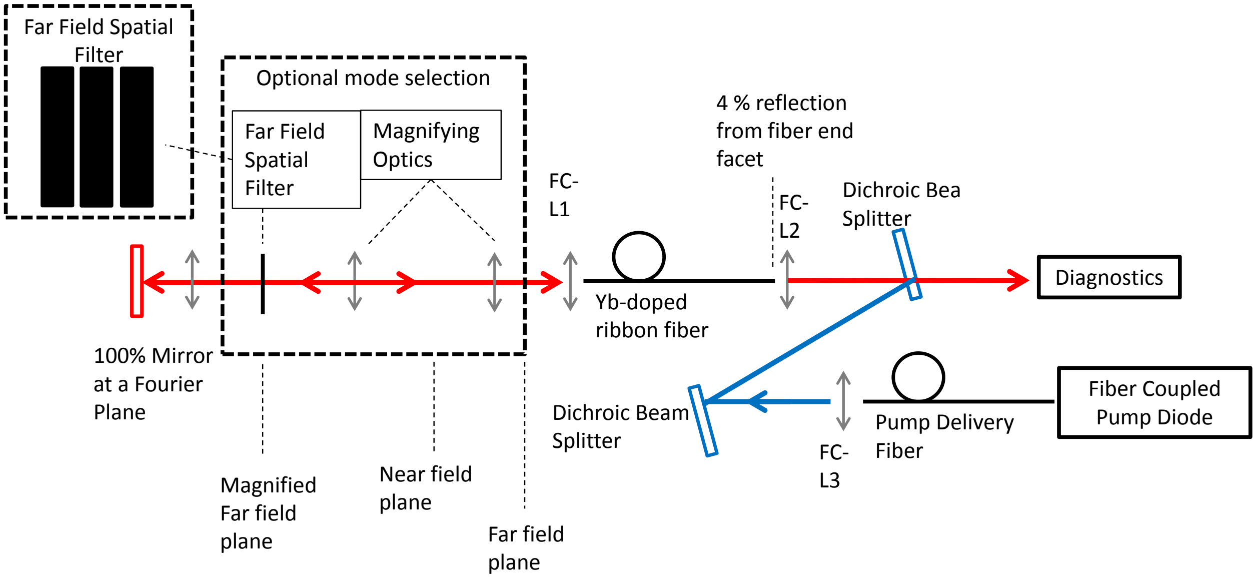



**Figure 21: Ribbon fiber oscillator experimental setup with optional mode selection. The cross-section of the spatial filter (top left) is designed such that only the two far field lobes of the desired mode can pass the filter**

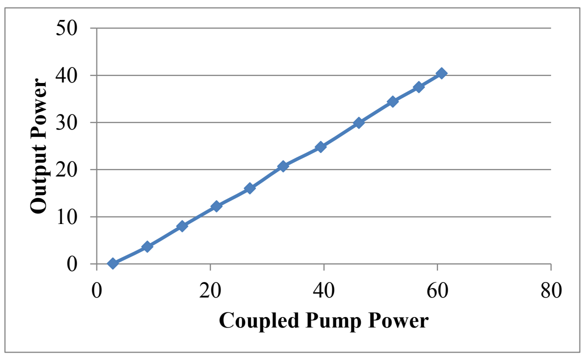



**Figure 22: Output power v.s. coupled pump power for a multimode ribbon fiber oscillator showing 71% slope efficiency.**

## Single mode selection and oscillation

Ideally, a ribbon fiber oscillator would LASE in a single mode such that the output could be converted into the fundamental mode outside of the cavity. The near field of the oscillator manifests as a superposition of all oscillating transverse modes, and so it is difficult to select only one. In the far field, however, the individual modes are spatially separated, and a simple one dimensional amplitude mask can be placed in the far field such that the two primary lobes of the desired mode are transmitted and all other modes are blocked. Because not all of the power in the mode is confined to the two primary far field lobes, about 12% of the power in the desired mode is blocked with each round trip in the cavity. This loss in mode power and purity adds to the cavity loss, reduces efficiency, and limits the return mode purity but still provides intra-cavity selection a single high order ribbon fiber mode. Alternative masking methods, such as a near field phase or amplitude mask may add purity and efficiency.

Even with these drawbacks, a single high order mode ribbon fiber oscillator has been demonstrated. Figure  shows the output power v.s. coupled pump power for single mode operation with 44% slope efficiency up to 5 W. Higher power studies are possible as well as improved cavities and slope efficiency, but have not yet been fully explored. Figure  shows the near and far field of the oscillating mode for a series of different power levels showing a nearly unchanged modal profile. As with the amplifier experiment, the small amount of power in a polluting mode, as can be seen in the far field profile, begins to grow slightly as the power is increased, but does not overtake the initial mode. Further experiments could better isolate the single higher order mode with better amplitude masks, and improved pointing stability of the beam on the mode selection side of the oscillator.

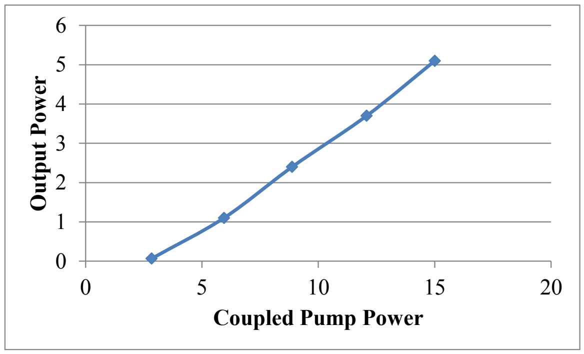



**Figure 23: Ribbon fiber oscillator operating in a single high order mode. Output power v.s. coupled pump power showing a slope efficiency of 44 %**

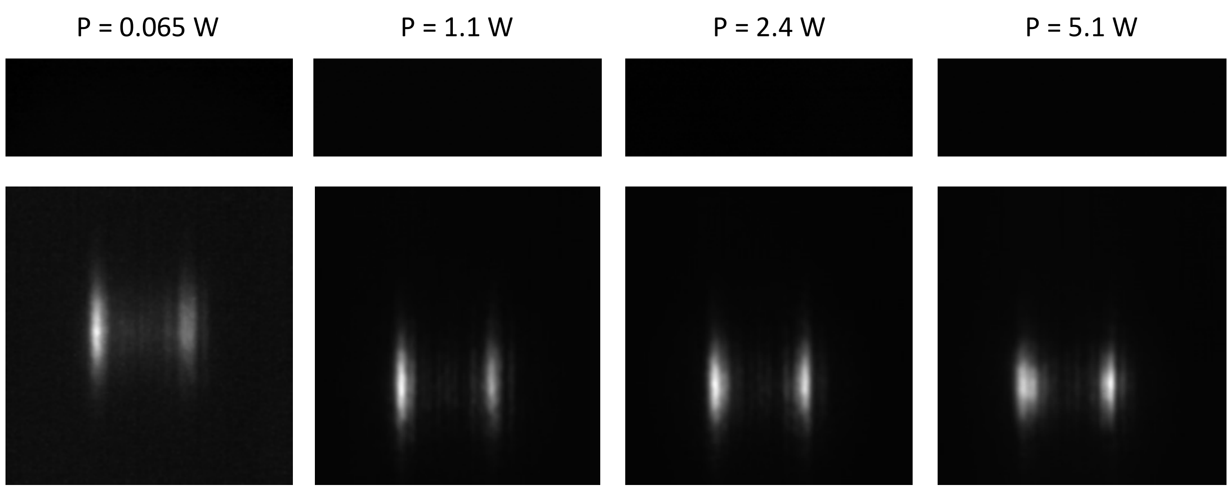



**Figure 24: Near field (top) and far field (bottom) of a single high order mode ribbon fiber oscillator. The modal purity is nearly unchanged from threshold to 5 W**

## Summary and Conclusions

Ribbon fiber lasers and amplifiers which have rectangular cross-section cores show great promise in increasing the fundamentally limited power that can be achieved with circular core fiber lasers and amplifiers. Circular core fiber amplifiers are limited to 2 kW (narrowband), or 36 kW (broadband) by a combination of thermal lensing and stimulated Brillouin scattering (narrowband), or stimulated Raman scattering (broadband). The broadband case is further limited to just over 10 kW if the bending limit is also considered.

We have reported a passive photonic crystal ribbon fiber and demonstrated a novel technique for single high order mode illumination with 90% mode purity. An active, air clad Ytterbium doped ribbon core fiber is also reported and operated as an amplifier in a single high order mode. The ribbon fiber amplifier achieved 50% slope efficiency, > 24 dB of gain, and 10.5 W of output power. Single high order mode operation was maintained up to approximately the 20 dB gain level.

A multimode ribbon fiber oscillator was also demonstrated which showed 71% slope efficiency, and an output power of 40 W. Intra-cavity mode selection was also employed and the oscillator operated in a single high order ribbon mode with the mode remaining mostly unchanged up to 5 W of output power. Higher power studies of a single mode ribbon fiber oscillator have not yet been fully explored.

The active fiber results displayed less than ideal modal profiles in which each lobe of the near field was not of equal magnitude. This is likely due to inconsistencies in the doping concentrations and refractive index of the core rods. For this reason, future ribbon core fibers should be guided via the photonic crystal structure as in the passive ribbon fiber reported above but with the active core rods index matched to the surrounding glass. Although there was no modal selectivity in the fiber, a novel mode launching technique was demonstrated to illuminate a single high order mode in the ribbon fiber, which was amplified to > 24 dB of gain and the mode remained pure until the amplifier approached saturation and the impurities began to grow. For this reason, future ribbon core fibers should also have active core rods selectively placed in the core in a designed such that it would have high mode selective gain as was previously proposed in [2,3].

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[i] IPG Photonics revenue figures from Yahoo Finance