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Ribbon Fiber Geometry for Power Scaling in Continuous Wave Fiber Lasers

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INTRODUCTION

Fiber lasers can be highly efficient and have been scaled to high output power levels. For example, IPG Photonics recently demonstrated a broad-bandwidth 10kW diffraction limited fiber laser [1] and Northrup Grumman described a single-frequency version at the 600W level [2]. The University of Southampton [3] recently reviewed the status and future prospects of high power fiber lasers.

Our analysis [4] of the ultimate scalability of conventional fiber lasers suggests the output power limit for broad-bandwidth (stimulated Raman scattering [SRS] limited) fiber lasers is in the tens of kW and in the few kW range for single-frequency (stimulated Brillouin scattering [SBS] limited) fiber lasers. All physical effects are considered in this analysis, but the most important ones are the non-linearities of SBS and SRS, thermal lensing and the limit to mode area caused by the need to bend the fiber laser into a practical package size. In order to raise the power thresholds at which non-linear effects limit fiber laser output power, it is desirable to increase the fiber core diameter and decrease the fiber length. On the other hand, to raise the power threshold at which thermal lensing limits the output power of a fiber laser, it is desirable to decrease the fiber core diameter and increase the fiber length. For the optimal choice of core diameter (possibly >90μm) and fiber length we find that wide-bandwidth fiber lasers are constrained by both these limits to 37kW of output power, while narrow-bandwidth fiber lasers are constrained to the 2kW level [4]. However, if the goal is to achieve diffraction limited output power, the fiber core diameter cannot be scaled arbitrarily without simultaneously reducing the NA. The waveguiding is then weakened to the point where the fiber cannot be bent without distorting and significantly shrinking the mode size. By using practical mode sizes in the 30-50μm range in our models, we find that the damage limited output power is 10-20kW for SRS limited fiber lasers.

The analysis of conventional fiber lasers suggests that scaling beyond 10-20kW from a single aperture fiber laser will require changing the functional form of the physical equations that govern the power scalability of optical fiber lasers. The effective area plays a key role in the equations that govern the performance of fiber lasers limited by nonlinear effects, while fiber laser limited by thermal lensing are highly geometry dependent. For example, a standard circular core yields a parabolic temperature profile and thus is naturally susceptible to thermal lensing. In contrast, a rectangular-core-based fiber laser that is cooled through the large faces has 1-D heat flow and can have little to no temperature variations across the long dimension of the core. Furthermore, such 1-D structures can be bent perpendicular to the narrow dimension with minimal to no distortion to the optical mode. A rectangular waveguide geometry provides a path to aperture scaling that is not inherently limited by thermal or bend effects. Our beam propagation method (BPM) calculations that suggest >100kW is possible from a 20μm X 500μm rectangular core based fiber laser.

Rectangular core fiber lasers have been considered [5-8]. Our efforts are strongly influenced by the ribbon fiber concept originally proposed and demonstrated by Beach [5-6]. He considers the rectangular core as a vehicle for the passive beam combination of a set of coupled single mode cores. In Beach's work, a higher-order-mode of the long dimension of the rectangular waveguide is selected by non-uniformly doping the core with a laser ion such that this single higher-order-mode has two times the gain coefficient of any of the other modes. Since he focuses on the coherent combination of core modes, his experiments and analysis does not consider the scaling limits of this approach or describe in detail how the desired higher order mode would be converted back to a standard, single lobe diffraction limited beam. Recently Guan, et al. [7], considered a geometry similar to Beach's ribbon fiber. Guan however focuses on nearest neighbor couplings and super-modes without considering the desirability of a uniform refractive index across the core. Shkunov, et al. [8] have also considered rectangular cores, but focus on propagation of the fundamental mode. This approach avoids mode conversion steps, but stable propagation of the fundamental mode may be more difficult to achieve in practice. OFS Laboratories [9] first detailed this distinction between the stability of propagation of the fundamental and higher order fiber modes for circularly symmetric fibers. The physics of propagation in rectangular fibers is similar.

In this paper we summarize recent progress towards the Beach vision of a ribbon fiber laser in which a higher order mode (ultimately gain selected) is employed to generate a large aperture, high power laser with the advantages of 1-D heat flow and bending in the small dimension. In this concept, mode transformations are employed to enable conversion of a beam from a standard single-lobe diffraction limited beam to a higher order mode for propagation in the rectangular waveguide and then transformed back to a standard beam. To date, we have commissioned the fabrication of several passive rectangular fibers from nLight Corporation to study the propagation of higher order modes and their conversion to and from standard TEM_{00} beams. The status of these studies is discussed in the next section. However, to realize gain selection it is necessary to fabricate a fiber with a patterned gain structure. We plan to achieve this goal is via construction of a photonic crystal ribbon fiber whose design is presented below.

PASSIVE RECTANGULAR CORE FIBER STUDIES

In order to study beam propagation and mode conversion in rectangular core fibers, we commissioned a series of fibers from nLight Corporation. The first two fibers have a round outer diameter and the final fiber has flats on the outside of the glass keyed to the rectangular geometry. The fibers have an outer glass diameter of 250µm. For the fiber with the flats this corresponds to the longest outer dimension. All the fibers have a mode-stripping coating so that only the core guides light. Figure 1 shows a picture of the end faces of these three fibers.

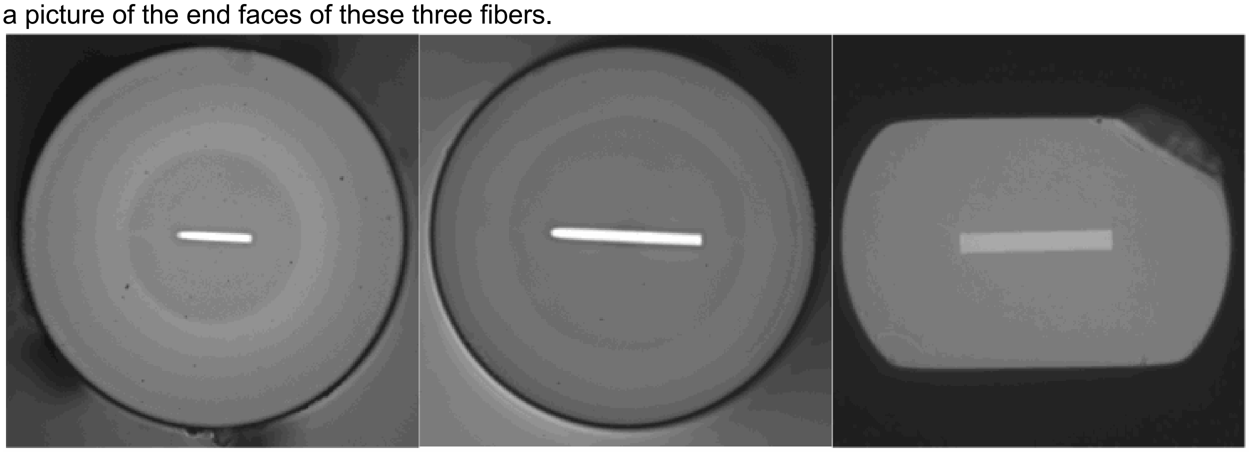

Figure 1. End faces of passive ribbon fibers fabricated by nLight Corporation. All have an outer glass width of 250µm. The three core sizes and NAs are from left to right: 5µm X 50µm (0.1NA), 8µm X 100µm (0.1NA) and 12.5µm X 100µm (0.08NA).

Quality of these fibers improved with each iteration in fabrication. Initial draws had issues with defects and high optical losses (as high as 120dB/km in the 5µm X 50µm fiber). However, later draws saw significant improvement with the most recent draw showing a background loss as low as 28dB/km at 1310nm. To date, no defects have been observed in the latest draw.

We have performed the most extensive optical testing on the 5μm X 50μm fiber. Light from a tunable 1μm fiber laser is coupled via free space into the core of this fiber using a pair of orthogonal cylindrical lenses that permit excitation of the fundamental mode of this fiber. The fiber is held roughly straight across is approximately 1m length. The fiber is oriented (as best as possible) so that the rectangular core has its long dimension perpendicular to the table. We employ a grooved mechanical plate following the work of Savin, et al. [10] to attempt to convert the fundamental mode to higher order modes via a strain induced long period grating (LPG) across the long dimension of the fiber core. The grooved mechanical plate has a 500μm pitch and can be rotated freely relative to the fiber to enable LPGs with varying groove density to be applied to the fiber. The benefit of this approach is that removal of the plate restores the fundamental mode at the output, allowing us to confirm that the launch conditions have not changed. Employing this technique allows observation of all modes of the fiber. Near and far field images of these modes are shown in figure 2 below.

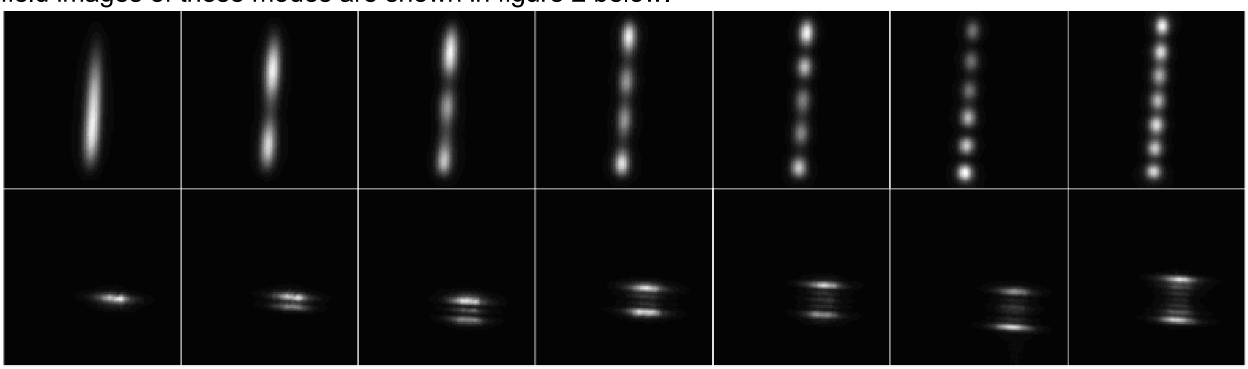

Figure 2. Near (top row) and far (bottom row) field images of the seven allowed waveguide modes of the 5μm X 50μm rectangular fiber.

The fundamental mode of the fiber is excited with >90% of the power in this mode. The conversion efficiency between this and any higher-order-mode is typically >70% while the remaining power is distributed amongst the other modes. Fractional mode content is determined via quantitative analysis of the near and far field data using a phase retrieval algorithm [11-12]. Intriguingly, higher fractional mode content can be achieved for the highest order mode via direct illumination of the fiber with a deliberately mis-aligned circular lens. However, this technique does not yield high coupling efficiency. In these photos coupling efficiency for the fundamental mode is around 60% with no measurable power lost in the mode conversion process.

While the goal of the above experiment is to achieve mode coupling via LPG effects, analysis of the measured angle of the grooved plate versus the calculated angle expected to achieve the correct period for the LPG to perform the mode conversion is in poor agreement. Thus we do not believe that we have successfully produced a LPG. We believe it is more likely the observed mode conversion occurs as a result of a single point perturbation at the edge of the plate. This theory is bolstered by the relatively broadband nature of the conversion (tens of nanometers), incomplete conversion of the fundamental to the target higher order mode, and our ability to achieve mode conversion with a groove-less plate. This phenomenon is under ongoing investigation. Qualitatively speaking, bending and pushing on the fiber being illuminated shows that the highest order mode is clearly more stable than the fundamental to small perturbations. We plan to quantify this further in the coming months.

DESIGN FOR A PHOTONIC CRYSTAL RIBBON FIBER

While it may be possible at low gains to operate a ribbon fiber with a uniformly doped core, such a core would have significant unsaturated gain at the nodes of the higher order mode. To enhance the stability of the system, it is desirable to dope only the peaks of the target mode. The most obvious method to create a structured gain fiber is to employ the production scheme associated with photonic crystal fibers. A photonic crystal ribbon fiber would consist of the standard array of holes with a line of defects. We have considered a range of designs with varying number of defects within a line of holes. We look at modal properties as a function of hole size. For easy comparison, we keep the width of the core fixed at 100μm and vary the size of a unit cell according to the number of defects (3, 5 or 7). We employ a variation of the code developed at the US Air Force Academy [13-14] running on LLNL supercomputers. Figure 3 shows a sample result.

The code is an implementation of the Finite Element Method (FEM) for the solution of fully vectorial electromagnetic problems in open waveguides, and provides the eigenmode profiles, their propagation constants and loss factors. It is ideally suited to hexagonally patterned PCF's. A structured mesh is used based on a hexagonal unit cell, which may contain one or two materials, and allows for simple and general specification of air-hole patterns. The code's architecture is greatly simplified by the use of a cell-based structured mesh. In particular the book-keeping associated with FEM is made feasible without recourse to specialized meshing packages. The eigen-solutions of the resulting sparse matrices are found by SLEPc, an eigensolver that is optimized for large parallel computers, such as those available at the LLNL supercomputing facility. Using one such machine, the solution below is obtained on one node with 12 CPUs in about five minutes.

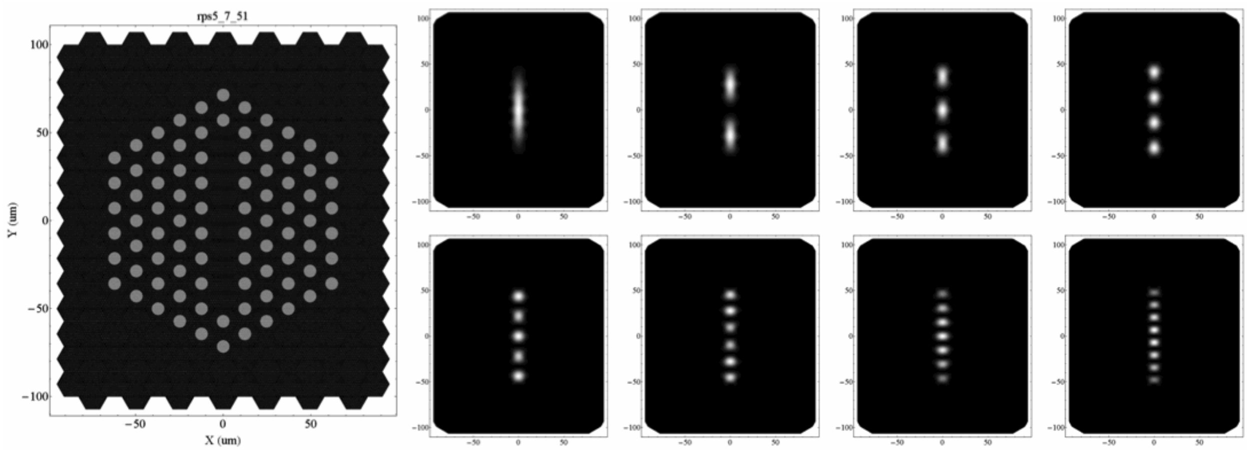

Figure 3. Example from PCF design study with 5 rings and 7 missing holes. The hole diameter is 51% of the spacing between the holes. The core size is then 100μm X 14.2μm and the design is shown on the far left of the figure. The eight allowed core modes are shown on the right side of the figure.

The most interesting feature of the example design is that the mode with four lobes appears to be the most uniform mode with equal power in each lobe. It also clearly shows the 4 rods where gain glass rather than passive glass is desirable. Surprisingly, the 7 lobe mode does not have a uniform distribution of power between modes and thus appears less desirable than the 4 lobe mode. The remainder of the design study follows this pattern where for N missing holes (where N is an odd number) the mode with (N+1)/2 lobes appears qualitatively to be superior to the others in terms of mode spacing and uniform distribution of power between lobes. The design study is in its initial phases and further optimization is expected in the coming months.

CONCLUSIONS AND FUTURE WORK

We believe that rectangular core fibers offer a promising route to efficient, high power continuous wave fiber lasers. Realizing this promise requires significant work including development of efficient and high contrast mode converters between the fundamental and higher order modes, demonstration of laser action in the ribbon fibers and construction of gain structured ribbon fibers. Additional work is also proceeding in the modeling realm. We are continuing design work on photonic crystal ribbon fibers. We are also developing a Beam Propagation Method code to study the interaction of thermal, gain and non-linear effects and their possible impact on modal stability as a function of power.

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