High-power All-Fiber® components: The missing link for high power fiber lasers

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ABSTRACT

Fiber lasers have shown extraordinary progress in power level, reaching the kilowatt range. These results were achieved with large mode area fibers pumped with high power laser diodes coupled with bulk-optics. To enable the commercial development of these high power fiber lasers, we have demonstrated several All-Fiber® components, which replace the bulk-optic interface in the present laser configurations. These components include multimode fused fiber bundle combiners with or without signal fiber feed-through, Bragg gratings and mode field adaptors. The multimode fibers are used to couple several fiber pigtailed pump diodes to a double-clad fiber. Such combiners may contain a signal fiber to provide an input or output for the core modes of the double-clad fiber. Mode field adaptors perform fundamental mode matching between different core fibers. Bragg gratings are used as reflectors for the laser cavity. These components exhibit low-loss and high power handling of 200 Watts has been demonstrated. They enable the design of true high power single-mode All-Fiber® lasers that will be small, rugged and reliable.

Keywords: Fiber optics components, multimode fibers, double-clad fibers, multimode fiber couplers, high-power fiber lasers

1. INTRODUCTION

Double-clad fiber lasers have been around for several years and are well known for achieving far greater power outputs than core pump fiber laser architectures[1]. Several improvements over the past two years, including the development of large core double-clad fibers, have helped redefine the term "high-power" for fiber lasers. For the core pumped fiber lasers, one to five Watts of output power is considered high-power. Now, with commercial 100-Watts single-mode fiber lasers, laboratories' experiments achieving greater than 500 Watts in a single mode[2] and kilowatts in multimode combining of several fiber lasers, the power level of high-power fiber lasers is redefined. We now consider high-power to be 100 Watts or more. All of these new high-power fibers lasers are characterized by the power level itself, but also by the fact that most of them operate close to a nonlinear optical limit such as Brillouin, self phase modulation or close to the damage threshold of the silica matrix. The limiting factor depends on the laser output, whether it is continuous wave (CW) or pulsed operation. In the former, only the power level and wavelength are important, but in the latter, though average power is a factor, pulse peak power, duration and repetition rate can have significant effects. All of these limiting factors have, however, one common solution: expanding the core size will reduce the power density, thus reducing nonlinear effects and increasing threshold levels.

1.1. Large core double-clad fibers

A double-clad fiber is composed of a fiber core, that guides the signal, a first cladding that guides the pump laser power and a second cladding composed of either a lower index silica glass such as a fluorine doped glass or a fluorinated acrylate coating producing a large index step. Large core double-clad fibers are being developed in a variety of sizes. The cladding diameters are available from 125 µm to 600 µm or more. The larger claddings have enabled multiple-hundreds of Watts of pump power to be injected in the double-clad fiber. This additional pump power is converted in the gain fiber into more output power. Core sizes have grown for 5 µm for the single-mode fibers to 20 or 30 µm sizes to reduce the nonlinear effects. Of course, increasing the core size will create core waveguides that are no longer single-mode. The presence of higher order modes will cause degradation in the output beam quality and will reduce the gain efficiency of the amplifier. Thus, a lot of work has been aimed at producing low numerical aperture NA cores that permit single-mode operation for a larger diameter, or that reduces the number of guided modes in the fiber. It also allows a larger mode field diameter for a given core diameter than a higher index fiber and makes higher-order mode stripping possible by coiling the fiber. However, mode stripping implies losses of optical power. The lost power, especially in high power applications, must be handled very carefully because it can cause organic materials in the fiber laser assembly to catch fire and burn, destroying the laser. Thus, not exciting the higher order modes by having a good modal control is critical in high power fiber laser design and assemblies. Bulk optic coupling to the double-clad fiber can be used to adjust the mode excitation but this requires precise alignment and lacks compactness and robustness. These lasers are tabletop demonstrations and lack the reliability of existing lower power fiber lasers that use miniaturized coupling elements such as fiber optic components in their assemblies. Thus, there is a need for high-power handling, few-mode All-Fiber® components with good fundamental mode transmission to transform these laboratory demonstrations into commercial products.

1.2. High-power fiber laser architectures and components

Single-mode fiber optic components in low power fiber lasers will naturally optimize the transmission in the fundamental mode. There is intrinsically a new level of complexity in designing and handling a few-mode core, where even a splice can create higher order modes. Furthermore, these components will need to handle higher optical power. To better demonstrate what and where All-Fiber® optical components can play a role in higher-power fiber laser, we give examples of two simplified schematics of a fiber laser cavity (Fig. 1) and of a high power optical amplifier (Fig. 2).

As illustrated in Fig. 1, the basic double-clad fiber laser is composed of a gain double-clad fiber, a high power pump diode assembly that is fiber pigtailed to a large diameter fiber (400 µm to 800 µm diameters with numerical aperture typically of 0.22), bulk-optic coupling setup and mirrors. The gain fiber, a few meters long is generally spooled for space saving but also, in the case of the large-core few-mode fiber with a small numerical aperture (0.06), to filter out higher order modes. The coupling setup uses lenses to couple the light from the pump fiber into the cladding of the gain fiber and the laser wavelength from the core of the double-clad fiber is demultiplexed to a cavity mirror. At the other end of the gain fiber, there is output coupling optics for the output beam. A mirror can be used to form the laser cavity but because of the high gain in the fiber, a 4% reflection on the cleaved end-face is enough. These bulk optic parts can be replaced by fiber optic components that are more compact, insensitive to contamination of the optical interface and misalignment. As illustrated in the bottom drawing of Fig. 1, the mirror is replaced by a high reflectivity Bragg grating. This eliminates the need to demultiplex the core signal. The input fiber can be directly coupled to the gain fiber, or, for the purpose of making a smaller size, more compact pump supply, the high-power laser diode assembly can be replaced by a number N of individually packaged diodes or bars, pigtailed to N smaller pump fibers that can be combined into a multimode fused fiber bundle that is then spliced to the gain fiber.

In Fig. 2, we illustrate a fiber amplifier than can be used to amplify an input laser signal. This configuration can also produce high-power laser outputs because of the large amount of pump power available. In this example, a signal coming from a smaller core fiber is coupled into the large core of the gain fiber. The core must be larger because after the amplification, the power at the output of the amplifier would produce nonlinear effects in the smaller core. In this configuration, there are no mirrors, but the pump power must still be coupled and multiplexed in the gain fiber as in the above-mentioned laser configuration. The optic at the input must adapt the mode field diameter from the small fiber to the large core fiber. At the output, the laser signal is demultiplexed by a dichroic filter. This configuration is a counter pump configuration where the signal is propagating in the opposite direction than the pump power. One can easily inverse this and create a co-pump configuration. Though the amplifier configuration requires approximately the same bulk optic parts than the laser, the fiber components required to replace the bulk optics are different. The multimode fused fiber bundle must have the additional feature of a feed-through fiber so that the signal can exit or enter the amplifier. Because of this central feed-through fiber, the pump fibers must be arranged symmetrically around this fiber for the bundle to work. It is thus preferable to work with several pumps, fiber pigtailed to smaller fibers, than with one large pump delivery fiber. If that is the only power source available, one must then use a special coupler to split that fiber into several smaller diameter fibers. Furthermore, it is essential that the modes of the different fiber cores are adapted through a mode adapter to minimize the loss. This adapter can be included in the fiber bundle in a co-pump configuration.

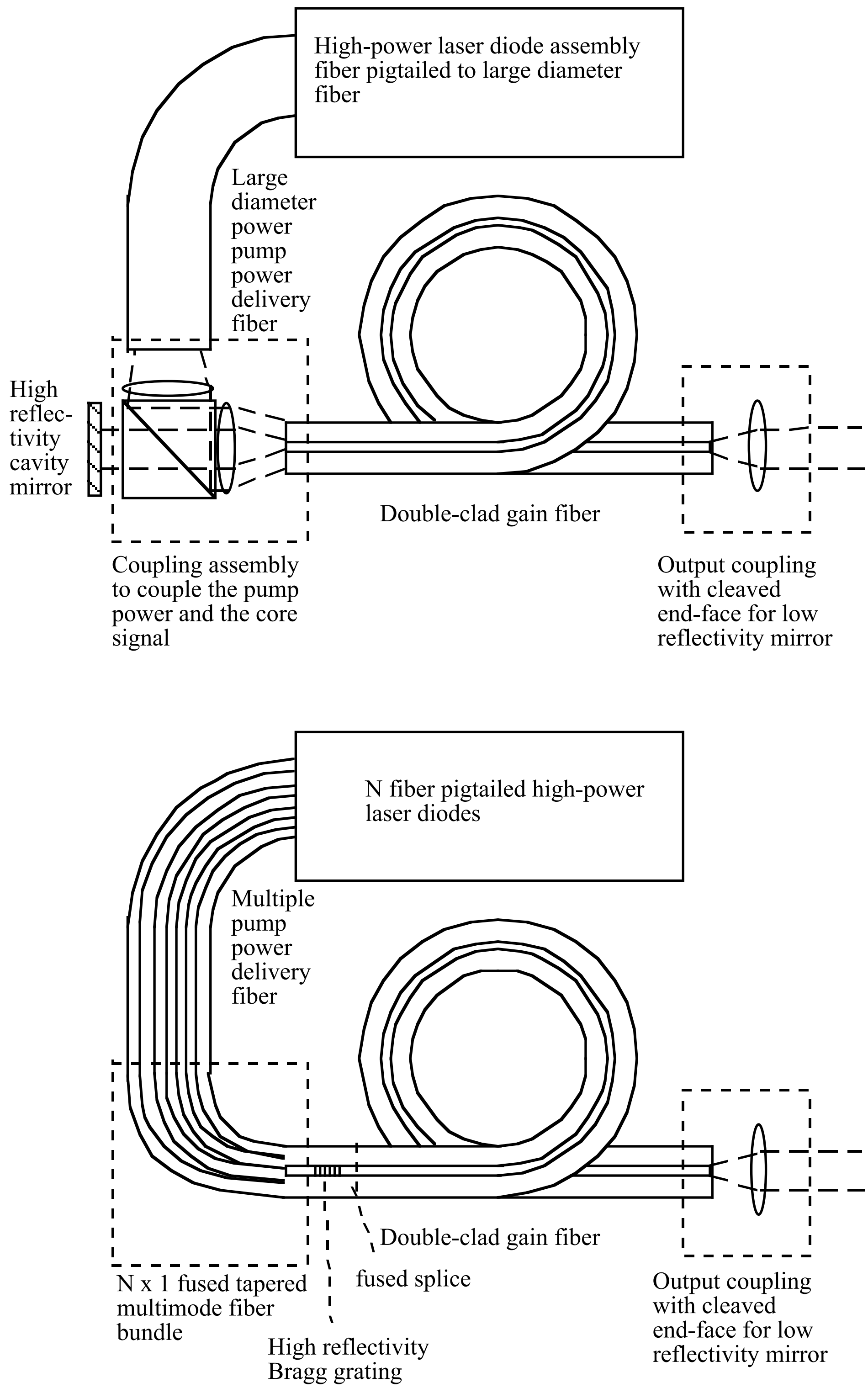


Figure 1: High-power large core double-clad fiber laser with bulk optic (top) and fiber optic parts (bottom).

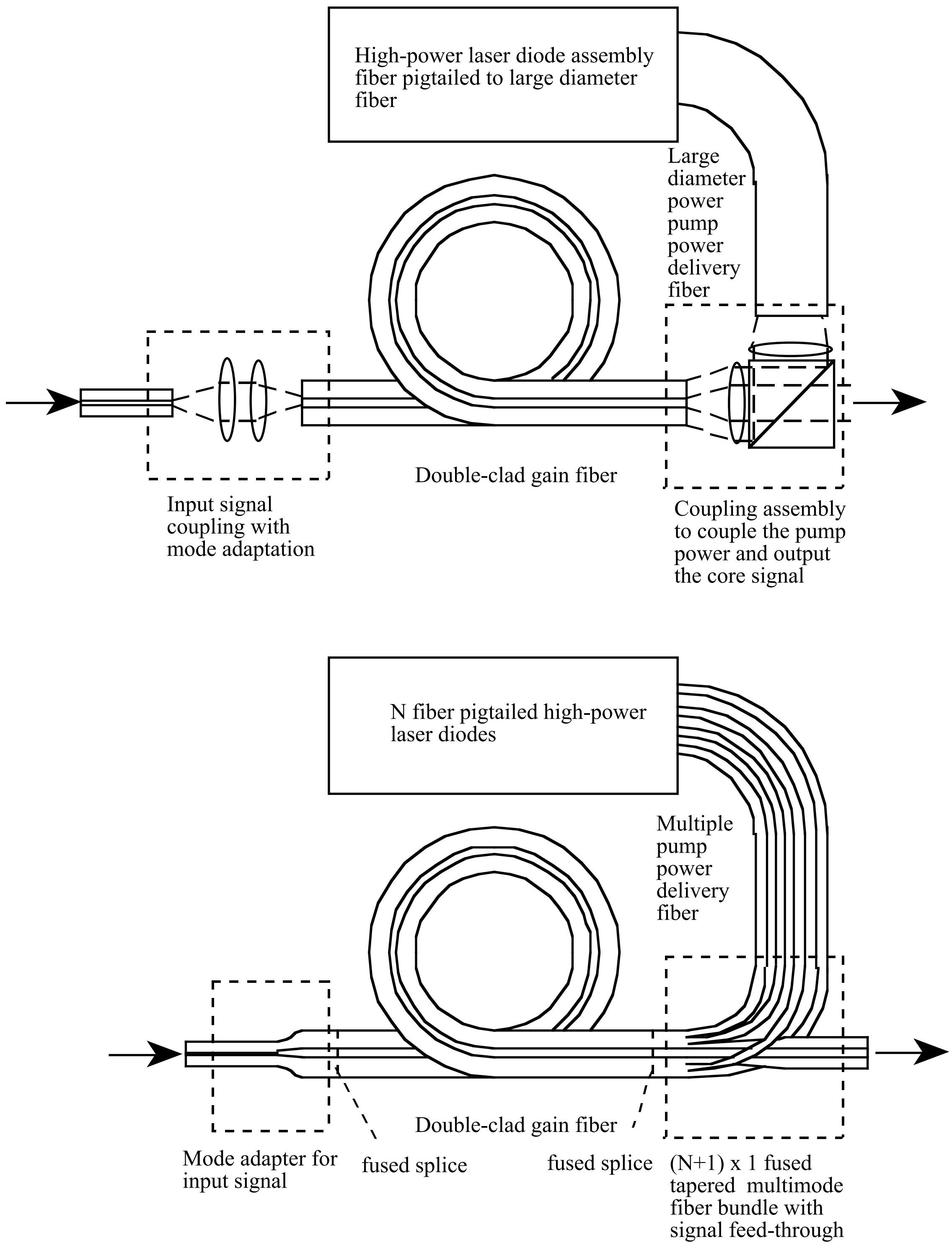


Figure 2: High-power large core double-clad fiber amplifier with bulk optic (top) and fiber optic parts (bottom).

Thus with the multimode fiber bundle combiner, with or without signal feed-through, the Bragg grating, the mode adaptors and the splices, one can replace all the bulk optic parts and build truly All-Fiber® lasers. All these fiber-based parts have existed in similar form for a number of years. Multimode fused fiber couplers date back more than 20 years[3]. Mode adaptors for connecting different single-mode core sizes and Bragg gratings have been around since the late 80's. Multimode fused and tapered fiber bundle combiners with single-mode feed-through were introduced in the late 90's[4]. All these parts must be redesigned for the high-power lasers with two very important characteristics in mind. First, except for the multimode-only combiners, they must be adapted to handle few-mode large fiber cores. This is a very significant element because modal content must be measured and controlled. It is not as simple as a single-mode-to-single-mode connection. High order modes create more loss. The second characteristic is also related to loss. These new components must handle very high power and thus be able to dissipate several Watts to 100 Watts of lost power. Because of these requirements and other optical limitations, we will describe, in the following two sections, some design rules and example of components that will enable All-Fiber® laser designs. Finally, we will discuss high-power handling and then provide an overall conclusion.

2. FUSED FIBER BUNDLE COMBINERS

Fused fiber bundle combiners replace the bulk optic couplings between the fiber pigtails from the pump laser diodes to the cladding of the double-clad fiber. There are two different types of multimode fused fiber combiners, without signal fiber feed-through, noted N x 1 (or 1 x N if used as a splitter) and with signal feed-through, noted (N+1) x 1.

2.1. N x 1 fused fiber bundle combiners

Multimode fused fiber bundle combiners are used to multiplex several multimode fiber pigtails into a single output fiber. They are used to combine several individual multimode fiber pigtails from large strip diodes or laser diode bars. These combiners are fabricated in a process similar to fused fiber couplers by bundling in parallel N multimode optical fibers that have been stripped of their polymer coatings and cleaned. The fibers are then laterally fused and tapered. Unlike the fused couplers, however, the fused structure is cleaved in the middle and spliced to the output fiber. To collect all the optical power from the input fiber to the output fiber, one must preserve brightness. This can be summarized in this simple formula:

$$\phi_b NA_b \leq \phi_o NA_o \quad (1)$$

where ϕ_b is the diameter of the fiber bundle before tapering, NA_b is the largest numerical aperture of the input fibers, ϕ_o is the core diameter of the output fiber and NA_o is the numerical aperture of the output fiber. The diameter of the bundle can be reduced by choosing close packed structures such as 7 or 19 fibers placed on a triangular grid, and by fusing the bundle, as shown in Table 2. For a complete fusing, $\phi_b = N^{1/2} \phi_i$ where ϕ_i is the diameter of an input fiber. Table 1 summarizes possible combiners made from standard multimode fibers, taking into consideration symmetry, close pack arrangement of the fiber bundle and feasibility for polymer clad fiber (PCF) with a numerical aperture of 0.46 (typical for double-clad fibers).

Input fibers\ Output fiber	125 µm PCF, NA =0.46	250 µm PCF, NA = 0.46	400 µm PCF, NA =0.46
105 / 125 µm, NA = 0.15	7 x 1	19 x 1	61 x 1
105 / 125 µm, NA = 0.22	4 x 1	7 x 1	37 x 1
200 / 220 µm, NA = 0.22	1 x 1	4 x 1	7 x 1
400 / 440 µm, NA = 0.46	N/A	1 x 1	3 x 1

Table 1: Multimode fused fiber bundle combiner arrangement as a function of input fibers (indicated with core/cladding diameters and numerical aperture). A 1 x 1 configuration indicates that a single input fiber can be tapered down and spliced to the output fiber without loss.

As can be seen in the results in Table 2, very low loss is achievable for the close pack 7 x 1 and 19 x 1 configurations. They are closer to a circular transverse profile and are thus easier to fuse. Furthermore, because the splicing process can introduce small defects that increase slightly the effective numerical aperture, configurations that have some margins with regards to Eq. 1 will have lower loss. These results were measured with fully filled conditions for the input fibers. If the fibers are underfilled due to the laser diodes launch conditions, these losses will be lower.

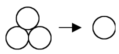
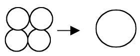
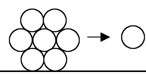
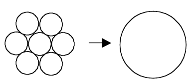
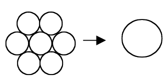
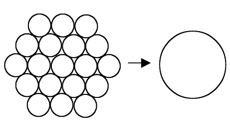
Configuration	Input fibers	Output fiber	Average insertion loss (dB)
2x1 	105/125 µm, NA= 0.12	105/125 µm, NA= 0.22	0.8
3x1 	400/440 µm, NA= 0.22	400 µm, NA= 0.46	0.75
4x1 	200/220 µm, NA= 0.22	400/420 µm, NA= 0.22	0.67
7x1 	105/125 µm, NA= 0.15	125 µm, NA= 0.46	0.32
7x1 	105/125 µm, NA= 0.22	400/440 µm, NA= 0.22	0.25
7x1 	200/220 µm, NA= 0.22	400 µm, NA= 0.46	0.09
19x1 	105/125 µm, NA= 0.22	400 µm, NA= 0.46	0.1

Table 2: Experimental results on N x 1 multimode combiners. The indicated insertion losses are averages over all the ports, measured in fully filled conditions.

1.2. 1 x N fused fiber bundle splitters

Furthermore, one can build a 1 x N fused fiber bundle to split the power instead of combining it. These components differ from standard multimode fused fiber couplers that have identical input and output fibers. Here, the goal is to split the power without losing brightness. Thus, the numerical aperture of the output fibers is the same as the input fiber and the transverse area of the output fiber bundle is close to the area of the input fiber. These components need to be particularly robust to high power handling because they will have more loss than a N x 1 combiner and they will be used to split large fiber pigtailed diode arrays which have a hundred watts to kilowatts of power. This power can then be recombined in a (N+1) x 1 combiner in a double-clad fiber. Two results are summarized in Table 3. In the 1 x 4 splitter, since the optical cladding was not removed from the output fiber, one would expect a loss due to this interstitial cladding to be around 0.65 dB, which is in agreement with the 0.86 average insertion loss measured in the component under overfilled condition. The losses are more important in the 1 x 7 case since additional interstitial loss occurs, due to the output fiber being too small to completely fill the 600 µm fiber.

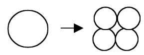
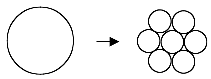
Configuration	Input fiber	Output fibers	Average insertion loss (dB)
1x4 	400/420 µm, NA= 0.22	200/220 µm, NA= 0.22	0.86
1x7 	600/660 µm, NA=0.22	200/220 µm, NA= 0.22	1.15

Table 3: Experimental results of 1 x N fused fiber bundle splitter

1.3. (N+1) x 1 fused fiber bundle combiners

A (N+1) x 1 fused fiber bundle combiner has a fiber bundle where the central fiber is replaced with a signal fiber. Furthermore, these combiners are used exclusively with double-clad fibers. However, due to production costs and measurement issues, the output double-clad fiber is not the double-clad gain fiber itself but a none-rare-earth-doped version with a matching index profile. The signal fiber is part of the bundle and is fused and tapered with the rest of the bundle. For high power lasers using large core double-clad fibers, this signal fiber is not single-mode. Thus, a bad connection from the signal fiber to the core of the double-clad fiber will cause losses as high order modes are excited. Furthermore, in a co-pumped configuration, these higher order modes will be amplified in the gain fiber thus reducing the gain in the fundamental mode, even if coiling the gain fiber filters them out. In a counter-pumped configuration, the higher order mode will degrade the quality of the beam output. By reducing the tapering of the signal fiber in the bundle and by a careful fusion process, better control of the modal content was obtained in the coupler. A bad mode matching can also be caused by an asymmetrical fusion. This is the main reason why the closed packed configuration was chosen. In Table 4, we show two different (6+1) x 1 combiners. In the near field pictures of the output field, one can see the effect of a slight misalignment in the upper case, exciting LP_{11}, the 20 µm core (NA = 0.06) being double-mode at 1064 nm. The difference in the modal content explains the fundamental mode loss of approximately 1 dB compared with better than 0.3 dB in the other sample. The loss from the multimode pump fibers was better than 0.1 dB.

Furthermore, because the output double-clad fiber is not the gain fiber, it can be designed to be photosensitive. A Bragg grating can thus be written in the core. Like any Bragg grating in few-mode fibers, this grating will reflect the different modes at different wavelengths. With proper care, the grating can thus both act us a reflector and a mode filter.

3. MODE ADAPTORS

Another important component for the high-power fiber lasers are the mode adaptors. They convert the fundamental mode size from one fiber to another. There are different ways of adapting the modes. Firstly, by heating the fiber, the core dopants can be diffused, thus changing the size of the mode field. Secondly, the fiber can be tapered thus changing the core size. Finally, one can use a combination of both approaches. Whatever method used, the goal is to preserve the energy in the fundamental mode, by making the transition in the mode adaptor adiabatic. This may not be such a simple task depending on the core sizes and numerical apertures to match. As can be seen in Table 5, several examples of mode converters are given from Puremode 1060 or SMF-28 fibers to different 20 µm core fibers with different numerical aperture and cladding diameters. We give one example of the effect of the LP_{11} mode on the intensity profile.

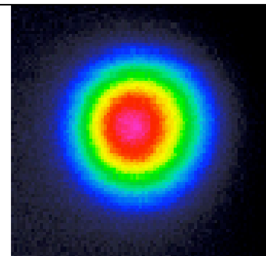
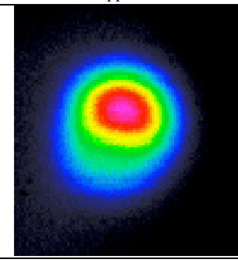
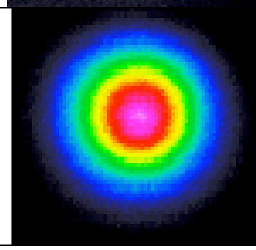
Configu-ration	Input pump fibers	Fibre signal	Double-clad fiber	Fundamental mode	Deformation due to LP_{11} mode
(6+1)x1	200/220 µm, NA= 0.22	20/125 µm, NA = 0.06	20/400 µm, NA = 0.06/0.46		
(6+1)x1	105/125 µm, NA= 0.22	20/125 µm, NA = 0.11	20/200 µm, NA = 0.11/0.46		

Table 4: (6+1) x 1 fused fiber bundle combiner with 20 µm core feed-through signal fiber. The measurement wavelengths were 1064 nm for the 0.06 NA signal fiber and 1585 nm for the 0.11 NA signal fiber.

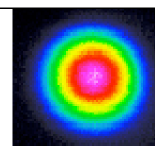
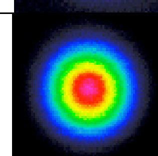
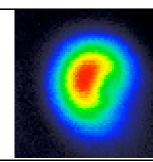
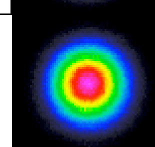
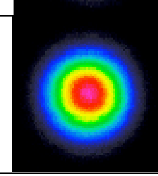
Mode adaptor	NA of large core fiber	Measurement wavelength (nm)	Minimum loss (dB) in the fundamental mode	Fundamental mode	Deformation due to LP_{11} mode
Puremode 1060 - 20/125 µm	0.06	1064	0.4-1.0		
Puremode 1060 - 20/400 µm	0.06	1064	0.3-1.0		
SMF28 - 20/125 µm	0.11	1585	0.3		
SMF28 - 20/200 µm	0.11	1585	0.2		

Table 5: Insertion loss and output power of different mode adaptors.

Furthermore, in co-pump amplifier configuration, the (N+1) x 1 combiner is at the input of the amplifier, where the mode adaptor is. One can actually integrate the mode adaptor into the combiner. The input signal fiber is thus a Puremode 1060 or SMF-28 single-mode fiber. The output is the large core double-clad fiber where the excitation of the fundamental mode is optimized inside the fused fiber bundle. However, this process is more difficult than for the mode adaptors because the conversion region is fused with the pump fibers. This can cause deformation of the core and of the mode. Two examples are given in Table 6. The effect of the strong fusion of six fibers around the signal fiber is very obvious in the second example where the mode intensity profile is deformed. This can be overcome with a proper fabrication process as illustrated in the same row.

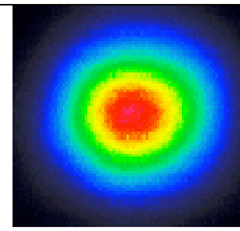
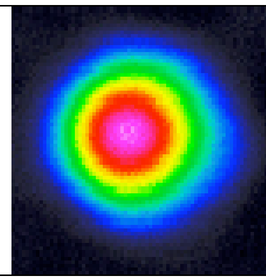
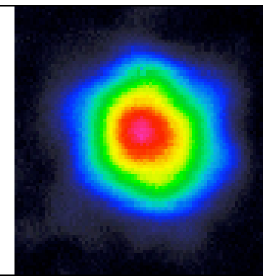
Configuration	Pump fiber	Fiber signal	Double-clad fiber	Fundamental mode	Deformation due to waveguide structure
(6+1)x1	105/125 µm, NA = 0.22	Puremode 1060	20/400 0.06		
(6+1)x1	200/220 µm, NA = 0.22	Puremode 1060	20/400 0.06		

Table 6: (6+1) x 1 fused fiber bundle combiners with integrated mode converters

4. HIGH POWER TESTS

All the previously presented components would have no use in high-power fiber lasers if they could not handle high power. However, testing these parts presents the problem of finding a high power, high brightness source that one can couple in the pump fibers or input fibers. The test was thus conducted using a high-power fiber laser. The gain fiber was coupled to a large fiber pigtailed laser diode assembly with bulk optic, as shown in Fig. 1. The output was coupled with a lens to one of the pump fiber inputs of the test sample, as shown in Fig. 3.

The test sample was a (2+1) x 1 combiner with 105/125 µm NA = 0.22 multimode input fibers, and had 0.34 dB insertion loss, about 10%. The power was increased by approximately 15 W increments and monitored at each step and the transmission of the test sample as a function of power is plotted in Fig. 4. Though the optical power at the output of the test sample was as stable as the laser, the temperature of the packaging was monitored with thermocouples over several minutes, until it stabilized. Even at 190 Watts of input power, the temperature rise was less than 3°C. Thus, because of its insertion loss, the component was dissipating about 20 Watts of power without any adverse effect. Furthermore, the linearity of the plot shows no degradation of the component.

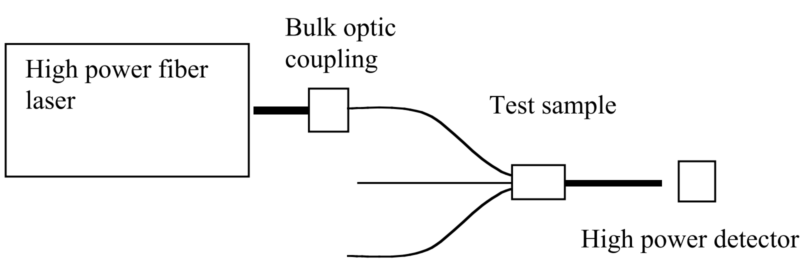


Fig. 3: High power test setup

Though not a complete high power test, the results shows the power handling capability of the fused fiber technology when properly packaged. The test was only limited by the power available from the high power fiber laser source. Other tests must be completed at higher power and with other components. In particular, other fabricated parts that have less than 3% loss and thus, if they can also dissipate 20 Watts without any degradation, could operate easily at more than 700 Watts.

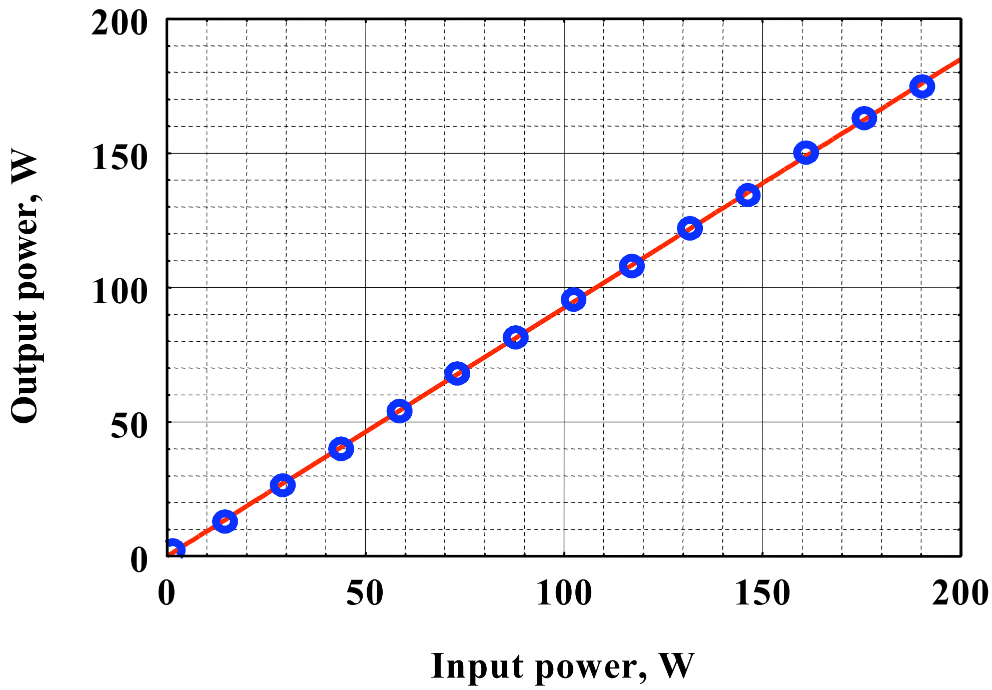


Fig. 4: High power test on a fused fiber bundle combiner. Prof. A. Galvanauskas and his group performed the test with a high power fiber laser source at the University of Michigan.

5. CONCLUSION

All-Fiber® components will play an important role in the commercialization of high-power fiber lasers. We have made several types of All-Fiber® components that can replace the bulk optic coupling assemblies for large core double clad fibers. The fused fiber bundle combiners are used to combine multiple diode lasers or diode laser bars in a single multimode fiber. Furthermore, with a large core feed through, they replace the dichroic thin film and lens assembly used to separate the signal from the pump laser input and couple into the double clad fiber. We have also built mode adaptors to transform the fundamental mode with minimal loss between single-mode and small core fibers to the large core fibers with 20 µm cores. We have furthermore integrated these mode adaptors with the fused fiber bundle, as well as Bragg gratings.

These fiber-optic components show good optical performances that are better than the equivalent bulk optic parts (i.e. less than 1 dB of loss). This lower loss is essential for the component to handle greater than 100 Watts of power. To that end, we have tested a sample fused fiber combiner with a signal fiber feed through with a high power fiber laser at 200 Watts and have measured no significant temperature increase in the part and no performance degradation. Because of its 10% loss, 20 watts were dissipated within the parts without problem. We thus expect similar parts with less than 3% loss to operate at powers above 700 Watts. This is by no means the limit of the technology; the experiments are limited by the available power from the test source.

Future work thus involves higher power testing, but also involves new components. In particular, 2 x 2 couplers for large core fibers are being developed. They can be used as tap couplers to monitor power in the high-power fiber laser or in assembly to combine outputs of fiber lasers or amplifiers. They retain single-mode like operation, even with the few-mode cores and can also be used as mode filters. They should have extremely low loss to operate in kilowatt regimes.

Thus, All-Fiber® components have the optical properties and power handling capabilities that will enable truly All-Fiber® lasers that will be more compact, more robust and reliable for high power lasers. They will require less maintenance, no misalignments being possible with the fiber splices. They can be made with a large selection of fiber sizes including large core, for which reasonable fundamental mode quality can be achieved. These All-Fiber® components will be well-suited for many fiber lasers, from CW to pulse, over a very wide range of applications.

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REFERENCES

1. P. Even, D. Pureur, "High power double clad fiber lasers: a review", *Proc. SPIE – Int. Soc. Opt. Eng.*, 4638 pp.1-12, 2002
2. J. Limpert, A. Liem, H. Zellmer, A. Tünnermann, "500 W continuous-wave fibre laser with excellent beam quality", *Elect. Lett.* 39(**8**) p.645, 2003
3. D. C. Johnson, B. Kawasaki, K. O. Hill, "Low-loss star coupler for optical fibre systems", *US patent* 4,330,170, 1982
4. D. J. Digiovanni, A. J. Stentz, "Tapered fiber bundles for coupling light into and out of cladding-pumped fiber devices", *US patent* 5,864,644, 1999.