Monolithic High-Power Large Mode-Area Fiber Amplifiers

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Introduction:
Ytterbium-doped large mode areas (LMA) fibers have become an established high power laser medium in recent years. Numerous lab-based experiments have demonstrated the relevance of the technology to broadband (typically > 10 nm linewidth) single-mode fiber lasers operating at the kilowatt-level [1,2,3]. In addition, the higher stimulated Brilluoin (SBS) threshold in these LMA fibers has enabled > 200 W of single frequency output power based on master oscillator fiber amplifier configurations [4,5] again with single mode beam quality. Beam combining schemes have been demonstrated with the intention of taking these fiber laser building blocks to the level of 10’s of kilowatts [6,7]. These systems will require field-deployable, monolithic, high-power, single-frequency LMA amplifiers. In this paper we outline the recent progress on standardizing LMA fibers and the developments of the relevant couplers, pump sources, connectors and high-power endcaps for developing monolithic (all-in-fiber) LMA fiber amplifiers. We present results for a monolithic 220 W CW LMA single-frequency fiber amplifier based on a LMA 20/400 fiber geometry

Results and Discussion:
The current range of standard LMA fibers has become well defined through various commercial vendors and may be summarized with reference to Table 1. Fiber cores with diameters up to ~ 30 µm and NA ~ 0.06 have become the industry standard for LMA fibers with the ability to deliver good beam quality through preferential modal excitation [8] or coiling induced higher-order mode losses [9]. The addition of PANDA-style stress elements to make PM-LMA fibers has added to the application space for the fiber technology and enabled high power linear polarized fiber amplifiers both in the CW [10] and pulsed regimes [11]. The availability of fibers with large claddings (400 µm) and high NA (0.46) in conjunction with high brightness pump sources have featured in many of the high power results, in particular amplification of single frequency sources into the high power regime (hundreds of watts) a potential building block for coherent beam-combining [6], and fiber array phase-locking [7] experiments.

Table 1: Standard Yb-doped LMA fibers

Fiber Spec	20/400	30/400	30/250
NA	0.06	0.06	0.06
LP01 MFD	18 µm	24 µm	24 µm
Pump Abs. 915 (975 nm)	0.6dB/m (2.0)	1.0dB/m (3.3)	2.0dB/m(6.0)
Application	High power CW	High average power pulsed systems	Medium average power, high peak power pulsed systems

Another sign of maturity in the LMA fiber technology is the availability of standard support components with LMA compatible fiber pigtails. A critical component for the development of monolithic high power fiber amplifiers are the multimode pump combiners which also serve as signal multiplexers. These components are available with input fibers compatible with industry standard pigtail fibers on commercial high power diodes. One particular example is the (6+1) to 1 design consisting of LMA compatible 20/400 double-clad fiber on the output of the combiner with 200/220 0.22 NA pump delivery fibers (six) on the input side (see table 2). Signal feedthrough options are either standard single-mode fibers such as 1060-HP or 20 µm core LMA fibers depending on the configuration under investigation.

Table 2: Standard LMA Pump Combiner configurations

Number of Multimode Inputs	6	6	6
Number of Signal Ports	1	1	1
Number of DCF Ports	1	1	1
Pump Input Fiber Parameters core diameter/clad diameter NA	105 µm/125 µm 0.22	200 µm/220 µm 0.22	200 µm/220 µm 0.22
Signal Fiber Parameters core diameter/clad diameter NA	HI 1060 6 µm/125 µm 0.14	HI 1060 6 µm/125 µm 0.14	LMA-GDF-20/400 20 µm/400 µm 0.06/0.46
Power per Multimode Input[1]	15 W	50 W	50 W
Multimode Power Transfer Efficiency/Insertion loss	> 93 % / < 0.3 dB	> 93 % / < 0.3 dB	> 93 % / < 0.3 dB
Signal Insertion Loss	< 0.5 dB	< 0.5 dB	< 0.5 dB

High-brightness, fiber-coupled pump diodes compatible with pump combiners listed in Table 2 are now commercially available with industrial-grade reliability. These advancements in high-brightness pumps and high-power pump combiners have enabled the high-power, monolithic design shown in Figure 1. In this case, six, 50 W fiber-coupled pump diodes (200/220 0.22NA delivery fiber) operating at 975nm were combined to provide approximately 300 W of pump power without free-space optics. The pumps are water-cooled to provide good wavelength stability.

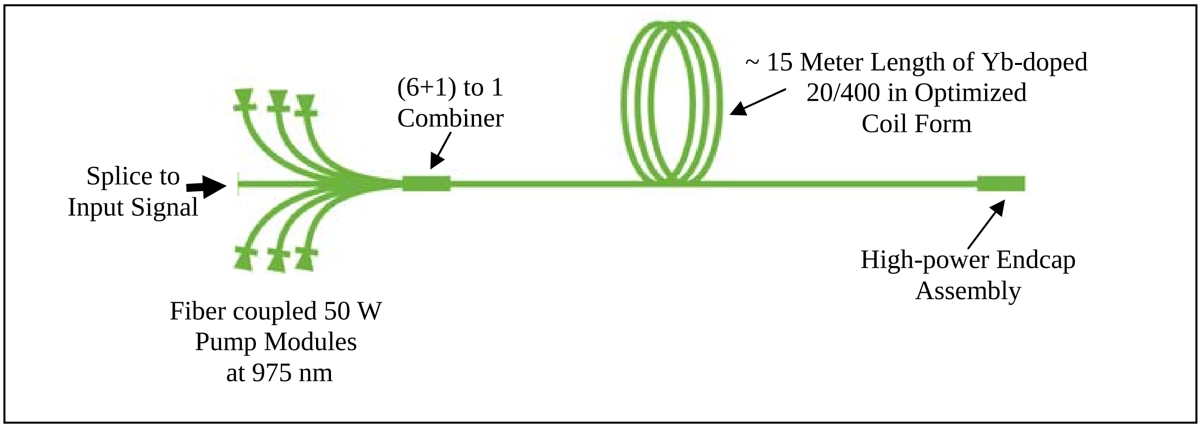

Figure 1: Schematic of > 200 W LMA monolithic fiber amplifier

Furthermore, the attraction of pumping with fiber coupled bars allows the use of high power connectorized pump sources as a means of delivering the pump power. This can be attractive for component recycling, adding additional pumps and upgrading the system design, since it allows a quick change of the pump sources without realignment of the rest of the system.

The gain fiber shown in Figure 1 is a LMA 20/400 Yb-doped fiber and the optimum length is ~ 15 meters for pumping at 975 nm with commercially available high power pump diodes. The fiber is coiled in an aluminum coil designed for heat dissipation. The coil is in intimate contact with the solid aluminum box, the base of which is water-cooled. The coil diameter of 10 cm is appropriate for preferential loss of higher-order modes. The fiber is designed to provide good beam quality.

At the output of the fiber device, angled endcap technology minimizes feedback into the amplifier and adequately expands the mode to ensure that the signal intensity is well below the surface damage threshold for the air-glass interface. The endcap (mounted in a standard connector form) technology is critical for stable operation of the amplifier with significantly reduced risk of surface damage in the deployed system.

Experimental results for the system design outlined above are shown in Figure 2, and demonstrate the applicability of these monolithic high power LMA fiber amplifiers to > 200 W CW powers. Although the power level is well below that demonstrated with broad linewidth fiber lasers and amplifiers [1-3], these LMA devices are applicable to amplifying single frequency input signals with coherence lengths suitable for further beam combining into the multi-kilowatt regime [6].

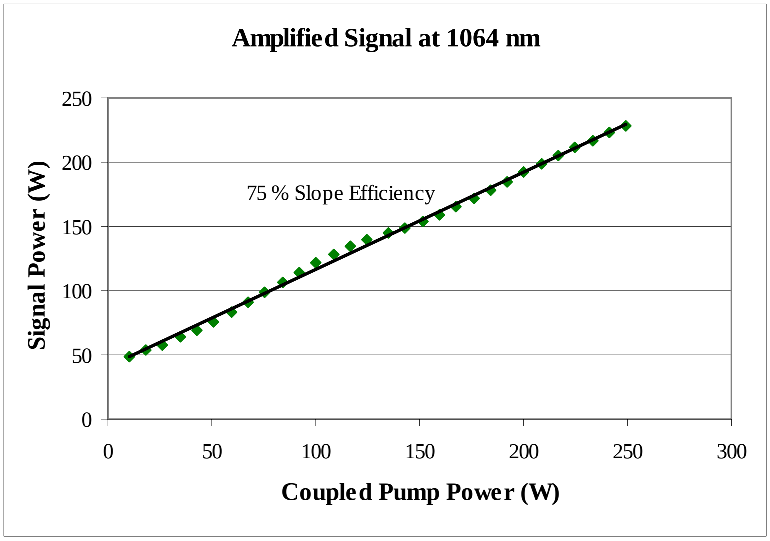

Figure 2: Output power from a monolithic LMA 20/400 fiber amplifier.

Figure 3: Monolithic LMA fiber including pump diodes and power supplies in a 19" rack mount system.

Conclusion:
LMA fiber technology has become an established means of power scaling fiber lasers and amplifiers. As the basic fiber design has become standardized, this has encouraged component manufacturers to design and build high power LMA compatible devices. We have demonstrated an example of this, by constructing a monolithic high power (220 W) CW fiber amplifier based on LMA fibers and components. Such amplifiers are suitable for amplifying single frequency input signals into the 200W watt regime.

Future Work:
Many beam-combining schemes require single-polarization output from the channels to be combined. PM-LMA fibers, both active and passive, are well established and have featured in many high power experiments recently. The passive versions are the basis for PM-LMA pump combiners which are currently being developed by

manufacturers and these PM-LMA pump combiners should become commercially available in the near future. Furthermore, the 220 W monolithic, LMA result described here is pump-power limited and not limited by the fiber or combiner technology. Higher brightness fiber-coupled pumps are being developed currently and will enable future power scaling to occur.

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