High Efficiency, Monolithic LMA Fiber Lasers and Amplifiers Operating at 1μm and 2μm Wavelengths

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Abstract
The development of large mode area (LMA) fibers, the compatible LMA fiber components and improvements in high brightness pump diodes together are enabling monolithic fiber lasers and amplifiers to operate at the kWatt power level. In this paper we describe recent component developments and present experimental results on monolithic LMA fiber amplifiers, developed around commercially available LMA fiber components, delivering 860W from ~1kW pump power when seeded with a broad linewidth (~1nm) source. For systems requiring narrow linewidth, we outline a monolithic PM-LMA fiber amplifier design capable of delivering ~180W with single mode, linearly polarized output when seeded with a single frequency (~10kHz) source at 1064nm. In the case of operation at the eyesafe wavelengths, we have developed monolithic fiber Bragg grating (FBG) based fiber laser operating around 2μm with 55% slope efficiency when pumped at 793nm and present experimental results at 110W output power (pump limited), delivering single mode beam quality at 2050nm.

Introduction
Monolithic, polarization-maintaining (PM) optical-fiber amplifiers represent a promising technology as building blocks for power scaling to 100 kW level through various coherent and spectral beam combining schemes [1]. The attraction of the monolithic platform is a robust all-fiber architecture reducing the number of free space components and eliminating air/glass interfaces wherever possible. Further advantages such as excellent beam quality, linearly-polarized output and narrow-linewidth amplification capability of the fiber amplifier are critical to many of these beam combining techniques if they are to reach the power levels required. Higher power monolithic fiber amplifiers operating in the kWatt power regime and capable of delivering these system parameters are attractive from an overall system design, reducing the number of elements in the array to reach a given power level. If practical, the option to operate at eyesafe wavelengths without sacrificing efficiency is also attractive in some scenarios.

Power scaling from LMA fiber amplifiers is largely dependent on three key technologies (a) the design of the LMA fibers, including PM versions that can operate at high power and deliver excellent beam quality when utilized in these systems, (b) LMA and PM components made from these fibers that operate at the kWatt power level with good efficiency and (c) compatible high power, high brightness pump diode sources at the critical wavelength around 976nm for pumping the Yb-doped fiber amplifier. While LMA fibers at 1μm have provided impressive output power numbers over the years [2-5], PM-LMA fiber-based components have only recently been manufactured which are capable of approaching the required power level [6]. Furthermore, it is important to show advances in the overall monolithic device architecture capable of operating reliably at power levels over 1kW, firstly through advances in the relevant fiber technology then subsequently the compatible LMA components and high brightness pump diodes. Given the high efficiency of the LMA fiber technology, we demonstrate ~860W output from the fiber amplifier (~85% slope efficiency) limited only by the available pump power. Furthermore, by limiting the fiber core diameter to ~22μm the beam quality is intrinsically very good due to the few moded nature of the LMA fiber design [7, 8].

Characterization of the monolithic fiber amplifier with 1kWatt of pump power has only been carried out with ~1nm linewidth seed source to date. However, at lower power levels free space experiments have now demonstrated 500W-1kW single frequency operation of a fiber amplifier although sometimes with multimode [9, 10] and typically unpolarized output. In this paper we demonstrate a monolithic PM LMA fiber amplifier delivering ~180W when seeded with single frequency input signal from commercially available fiber and components. In this case the limitations to the amplifier are no longer the available pump power but rather from stimulated Brillouin scattering (SBS) due to the narrow linewidth of the seed source. Improvements in the SBS threshold can readily be achieved by an increase in the mode field area of the LMA fiber and reduction in the fiber length. However in order to power scale this fiber architecture closer to the kWatt power level and maintain the single frequency input, SBS mitigation steps that do not deteriorate the beam quality should be implemented. Here we demonstrate a factor of 3x improvement in SBS threshold in a PM-LMA fiber amplifier by simple heating of a short section of fiber in the final amplifier stage to 80°C, well within the thermal capabilities of the fiber coating.

In addition to the research being carried out on power scaling fiber lasers and amplifiers at the 1µm wavelength using Yb-doped LMA fibers, we are also investigating power scaling highly efficient fiber devices at the eyesafe wavelengths around 2µm using Tm-doped silica fiber. Recent research has led to the optimization of the basic fiber composition by utilizing the efficient cross relaxation of excited Tm-ions under 790nm pumping [11, 12]. This work has demonstrated ~65% slope efficiency (793nm pumping) for Tm-fiber lasers operating around ~90W CW. These results were typically obtained from multimode fibers and free space cavities formed using bulk lenses and mirrors. However, a new generation of highly efficient Tm-doped fibers was recently introduced with the development of a true LMA fiber design operating at this wavelength [13]. This fiber uses the pedestal fiber design to reduce the NA of the Tm-doped core. Fabrication of photosensitive matching fibers for this, and subsequently fiber Bragg gratings (FBGs), allows us to investigate the performance of monolithic fiber laser cavities in highly efficient Tm-doped fibers for the first time. By using the FBG for wavelength and linewidth control, we can more accurately make 2µm fiber lasers achieving a specific (fixed) wavelength. This is critical for most practical applications such as pumping non-linear materials or Ho-doped crystals, atmospheric propagation within a given transmission window or medical lasers targeting a specific wavelength close to the water absorption peak.

Result on Monolithic Fiber Lasers and Amplifiers

860W Monolithic Fiber Amplifier at 1064nm

Scaling the available power from a single fiber laser into the kilowatt regime has been demonstrated by several groups, first in lab-based experiments involving free space optics and a simple linear laser cavity [2-5]. More recently, systems delivering single mode beam quality from a fiber MOPA fiber chain at ~1.5kW power level have become commercially available [14]. In this paper, we outline the development and performance of fibers and components that enable operation at power levels approaching the kWatt level as shown schematically in Figure 1.

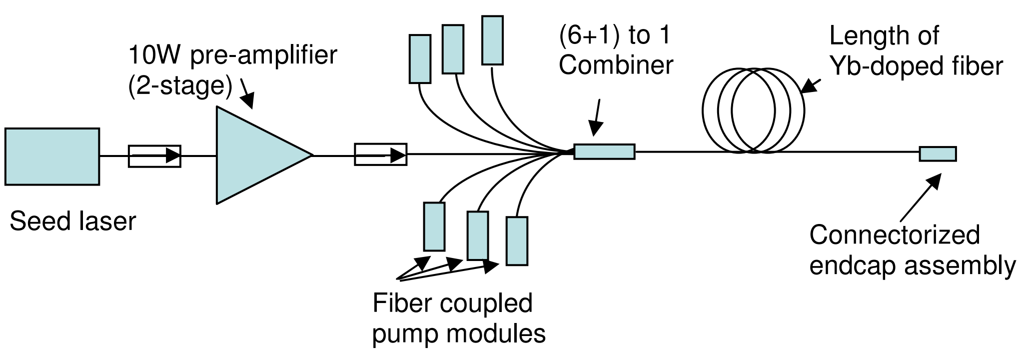

Figure 1: Schematic diagram of monolithic fiber amplifier chain with single mode beam quality.

Suppliers of high brightness fiber coupled pump diodes are now delivering modules compatible with the input pump legs to the available TFB couplers. These pump modules are spliced to the input pump legs of the TFB using standard commercially available splicers, with measured splice losses around 1% (higher values can be obtained in pump modules that deliver high amounts of cladding light launched into the delivery fiber). The overall power delivered through the TFB is >1kW and the spectrum for the combined pump source is shown in Figure 2, centered at 976nm with a FWHM of ~4nm. In our experiments, the pump modules were cooled in 2 banks of 3 modules each with a separate chiller.

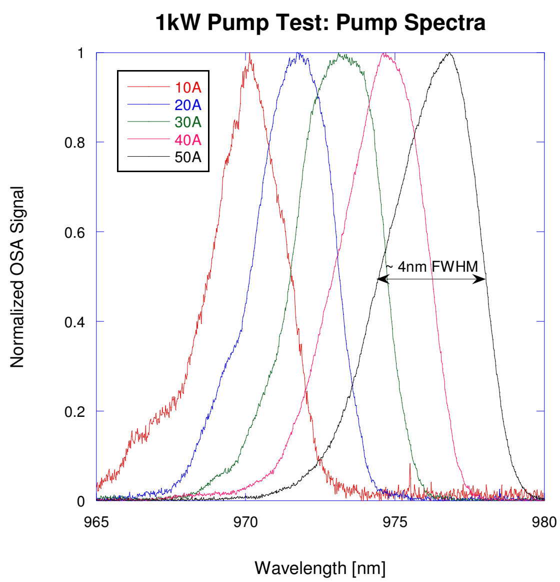

Figure 2: Spectra for the combined 1kW pump module used to pump the fiber amplifier in Figure 1. At full power the combined spectrum is ~4nm FWHM centered at 976nm.

The Yb-doped active fiber used in the amplifier experiments was based on a 22/400/440 triple clad fiber design and we used a fiber length of ~10m for the high power testing, corresponding to an absorption length of ~13dB at 976nm. This Yb-doped fiber was spliced to the output fiber of the TFB coupler. The slope efficiency for the final amplifier stage is shown in Figure 3 and we obtained a maximum of ~860W output for the available pump power and a slope efficiency of ~85% using a broad linewidth seed source with ~1nm FWHM.

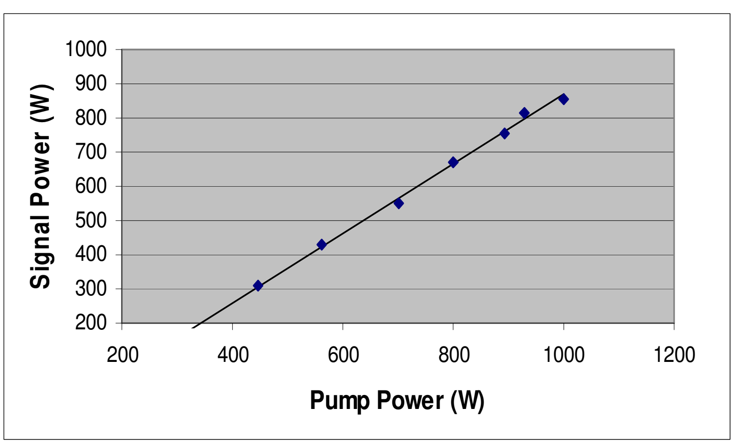

Figure 3: The monolithic amplifier in Figure 1 was characterized using a broad linewidth (~1nm) seed source and delivered 860W limited by the available pump power.

The spectrum of the amplifier output is shown in Figure 4 for around 4W seed power (24dB gain) at 1064nm. As yet, the amplifier has not been tested in a PM configuration although the couplers are already compatible with a PM design.

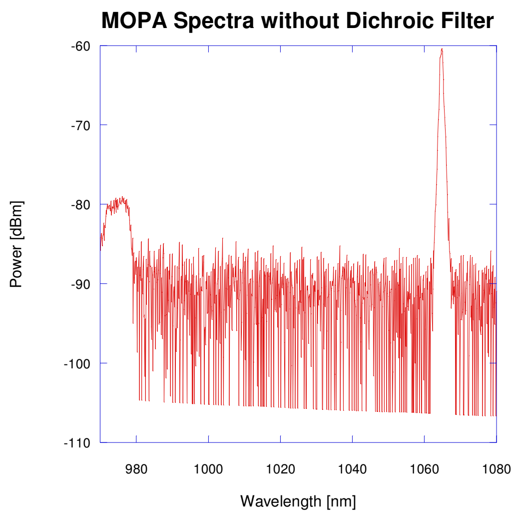

Figure 4: Spectrum from the amplifier at ~1kWatt pump power (860W output) and seeded with ~4W signal (~24dB gain). We see negligible ASE from the amplifier.

200W Monolithic PM Single Frequency Amplifier at 1064nm

The system described in Figure 1 has not yet been characterized in a PM amplifier design or with a narrow linewidth single frequency seed laser source. However, recent data using free space pumping of a power fiber amplifier stage has shown the capability to generate >500W output power from an LMA fiber amplifier (>40μm core diameter) seeded with a single frequency seed source [9, 10]. In one of these studies the thermal gradient provided by the high pump power in the fiber has been shown to increase the stimulated Brillouin scattering (SBS) threshold for the amplifiers by shifting the SBS gain spectrum at various sections (i.e. temperature gradient) along the fiber length, work subsequently validated by modeling [16, 17]. In Figure 5 below we outline the amplifier system we have developed for systematically characterizing the SBS threshold in various PM Yb-doped fibers. The results obtained for both PM-LMA 20/400 and 25/400 fiber amplifiers characterized in this way are shown in Figure 6.

In the initial test the Yb-doped fiber sections were coiled on cooling mandrels to maintain an even temperature distribution along the entire Yb-doped fiber length and the backscattered SBS power measured through the tap coupler. As shown in Figure 6, the SBS thresholds were 30W and 60W for the 20/400 and 25/400 fibers with similar pump absorption lengths of 13dB in both cases, corresponding to around 10m and 6m respectively. The improved SBS threshold for the PM 25/400 fiber can be attributed to the larger mode field area and shorter fiber length, largely as expected.

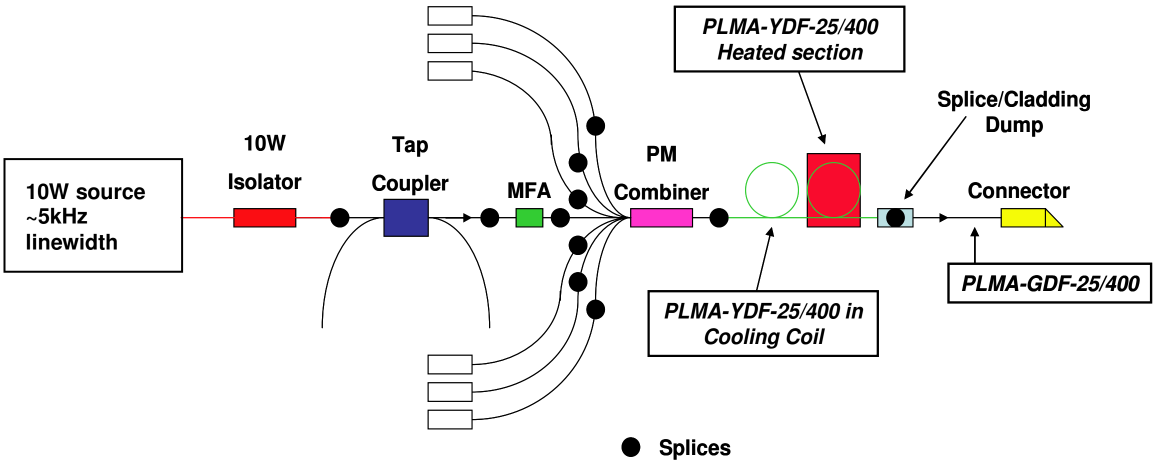

Figure 5: Schematic of the monolithic single frequency amplifier with heated coil section within the Yb-doped fiber amplifier stage to increase the SBS threshold for the system.

The next set of experiments consisted of heating a section of the Yb-doped fiber within the pumped amplifier section, whilst maintaining the rest of the fiber on a cooled mandrel, providing a step function in the temperature distribution. The temperature difference between the two sections (up to a maximum temperature of 80°C on the heated fiber section) and the length of the two sections was then adjusted to investigate the effect of the SBS threshold for the PM 25/400 fiber amplifier. Also included in this study were the effects of having various lengths of PM-25/400 delivery fiber spliced to the output of the amplifier. The results are shown in Figure 7 along with the effect of adding an undoped delivery fiber section to the amplifier that is not heated. The maximum SBS threshold was around ~180W for a heated section of fiber at 80°C (several meters) and the remainder cooled.

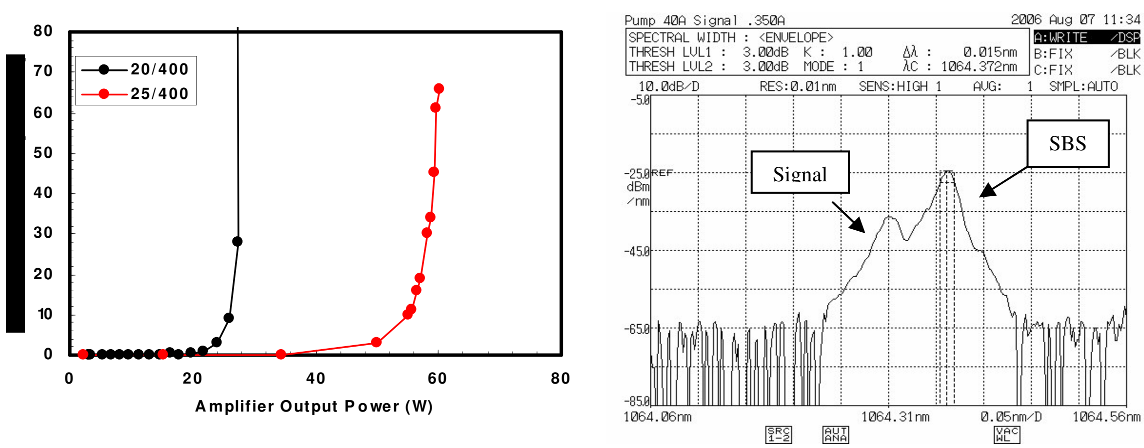

Figure 6: Measured SBS thresholds (backscattered SBS through tap coupler) for PM LMA 20/400 and 25/400 fibers under (cooled) coiled conditions. Thresholds are ~30W and 60W respectively, for 13dB pump absorption lengths in both cases (10m and 6.5m respectively). The spectrum for the backscattered signal is also shown.

PER and M^2 measurements on the packaged monolithic amplifier system showed >17dB PER and M^2 values better than 1.1 for the system at full power operation. The final packaged amplifier consists of a short length of delivery fiber with a beam expanding endcap to reduce surface damage. The delivery fiber section is not heated. The M^2 results at various power levels are shown in Table 1 for the complete system.

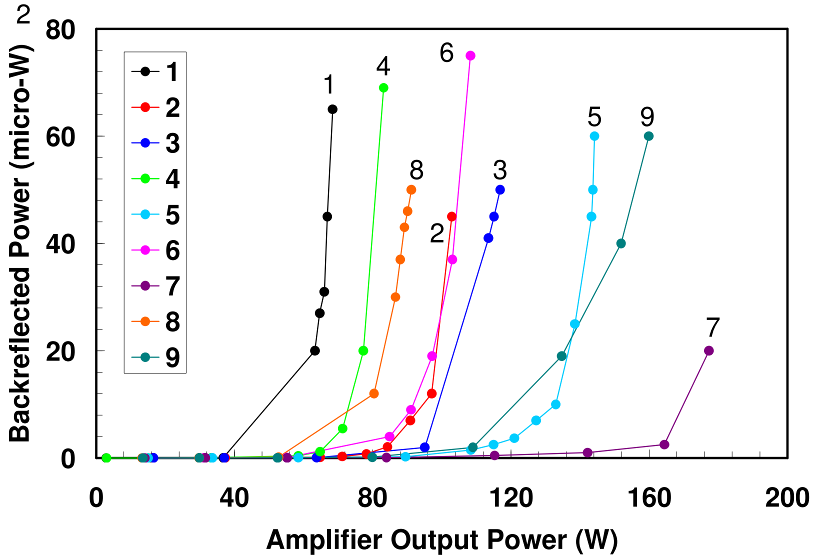

Figure 7: SBS threshold measurements for several different lengths of heated/cooled sections of PM 25/400 fibers showed a factor of 3x improvement from 60W to 180W for an optimized amplifier with several meters of Yb-doped fiber at 80°C, the rest of the doped fiber is coiled on a cooling mandrel.

ID	P (W)	Mx2	My2
1	68.4	1.07	1.07
2	102.9	1.05	1.04
3	116.9	1.07	1.07
4	83.2	1.07	1.06
6	108.3	1.05	1.06
7	177.0	1.15	1.13

Table 1: Measured M^2 for the PM LMA 25/400 fiber amplifier (with SBS mitigation) operating at various output power levels up to ~200W.

Highly Efficient 110W Monolithic Fiber Laser at 2µm

Fiber lasers operating at eyesafe wavelengths >1400nm are also very interesting for a number of applications. MOPA fiber chains similar to those described above operating with single frequency linewidth, linear polarized and single mode beam quality would be interesting building blocks for beam combing at eyesafe wavelengths. As yet these systems are not available at the hundreds Watt to 1kWatt power level. However, broad linewidth, high power fiber lasers operating at both 1550 and 1900nm are commercially available [14] but typically do not achieve the same efficiency as the systems operating at 1µm based on Yb-doped fibers. Current commercially available fiber lasers operating at 2µm are based on Tm-doped fibers resonantly pumped at ~1.6µm by an Er:Yb fiber laser, which is in turn diode pumped at ~960nm. Wall plug efficiencies in this case vary from 5-10% [14]. To date, the most efficient eyesafe fiber lasers have been demonstrated with free space fiber laser cavities based on optimized Tm-doped fibers lasing around 2µm with 793nm pump, and have demonstrated ~65% slope efficiency at power levels ~100W with 790nm pumping [11, 12] (see Figure 9). These free space cavities lack the wavelength control required for most applications and furthermore changes in linewidth and wavelength can be expected with increased pump power.

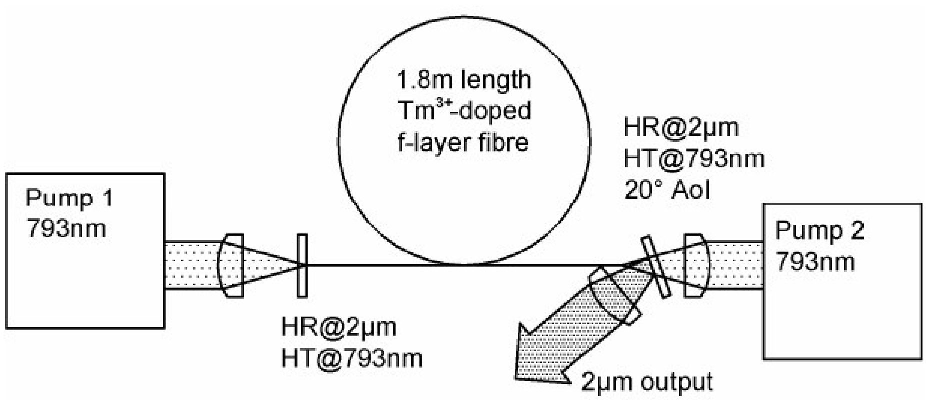

Figure 9. Efficient high power laser configuration

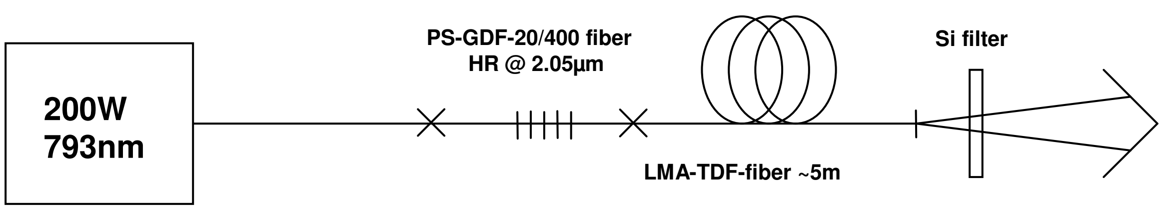

Figure 9, 10: Schematic of a free space laser cavity (taken from Frith et al., 2006 ref 6) and a fiber Bragg grating laser used in the current work to fix the operating wavelength.

The FBG based laser cavity we adopted is shown in Figure 10 and removes the need for the free space mirrors allowing direct end pumping of the fiber with a commercially available fiber coupled diode bar. The FBG high reflector is written in photosensitive fiber made to match the double-clad LMA Tm-doped fiber (25µm core diameter with 0.1NA and 400µm cladding). The grating pigtail fiber is spliced to the Tm-doped LMA fiber, which in the current experiments is then cleaved to form the laser cavity (~4% reflectivity output coupler).

The pump source is directly spliced to the fiber laser cavity in an end pumped configuration. The pump module is itself connectorized and the deliver fiber (400µm 0.22NA) is in turn spliced to the pigtail fiber of the FBG (as shown in Figure 10). This is the same configuration we have used for high power Yb-doped fiber lasers operating at 1030nm [18]. The development of output coupler FBGs is on-going and will clearly remove the need for the 4% reflection from the fiber end which is an undesirable configuration in almost all practical applications. The available FBGs were chosen for 2050nm because of the available phase mask and the linewdith of the laser is ~2.5nm at 110W as shown in Figure 11. The lasing is centered at 2050nm wavelength independent of the operating power over the range studied.

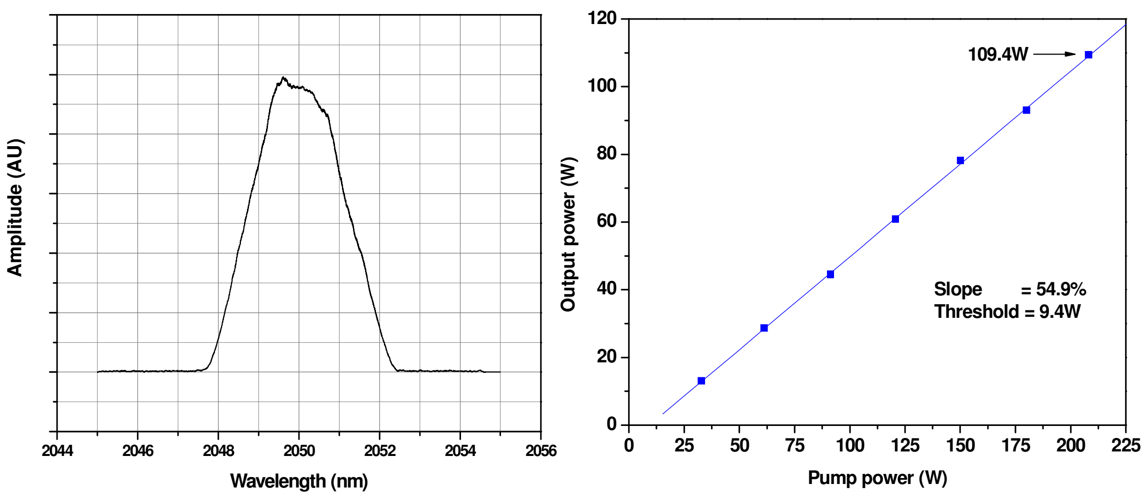

Figure 11: Linewidth from the FBG based Tm-fiber laser and slope efficiency. Operation up to 110W is linear and limited by the available pump power.

The slope efficiency of the laser cavity as shown in Figure 11 was around 55% and we achieved ~110W output power (after correcting for the Si filter loss at 2µm) from the laser without any sign of roll-off in the slope efficiency, indicating that the laser can readily operate at high output powers. The fiber was wound onto a mandrel of around 12cm diameter so as to facilitate conductive cooling of the fiber. The fiber length was ~5m. At full power the electrical to optical efficiency of the system was estimated to be ~17%. The output spectrum for the laser is essentially independent of the operating conditions and was centered at 2050nm with a FWHM of 2.1nm and ~2.5nm at 25W and 100W respectively. This is the highest efficiency, monolithic grating based eyesafe fiber laser we are currently aware of, capable of delivering >100W. Further improvements in the system are expected, including a monolithic 2µm fiber at higher power [19] and targeting specific wavelengths <2000nm.

The beam quality from the laser was robustly single transverse mode as shown in Figure 12 and a photograph of the benchtop system is shown in Figure 13. Although we have not collected long term lifetime data on the system, running the laser at CW power levels >100W for several days during the course of these experiments did not lead to significant degradation on the system, as has been noted for some Tm-doped fibers in the literature. Long term testing of these highly doped fibers is required to further determine if a long term degradation mechanism is present.

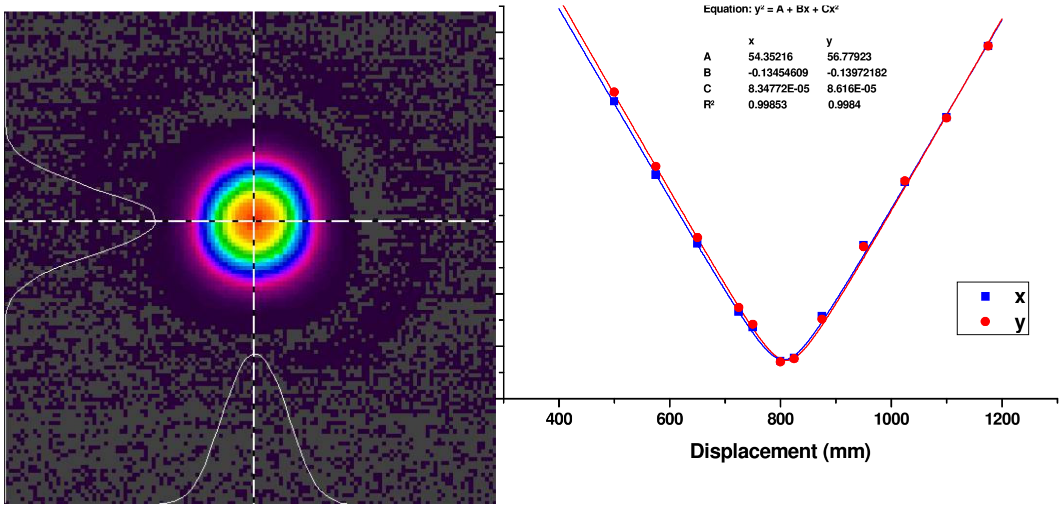

Figure 12: Beam quality data from the FBG based laser cavity (see Figure 10) at 2050nm.

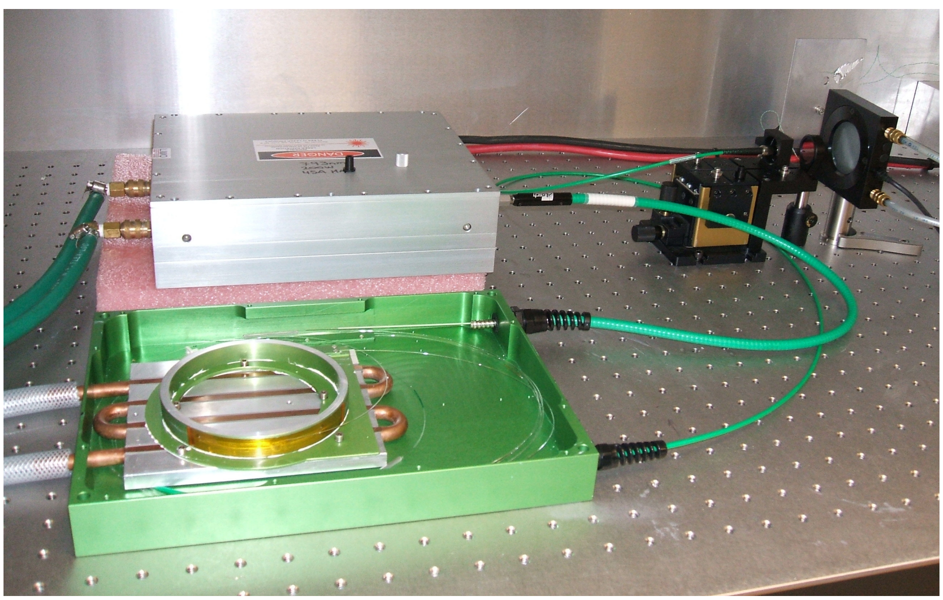

Figure 13: Photograph of the end pumped Tm-doped fiber laser cavity with ~200W (793nm) fiber coupled pump source and the monolithic FBG based cavity shown separately. In this case the pump is a connectorized LIMO pump module with 400µm 0.22NA delivery fiber.

Summary

The components, fiber and relevant pump sources for power scaling all-fiber, monolithic, high power fiber laser/amplifiers is progressing rapidly and enabling a wide range of system designs covering a varied application space. In this paper we used commercially available components and fibers to demonstrate a broad linewidth (~1nm) kWatt class monolithic fiber amplifier at 1064nm, a ~180W single mode, single frequency PM fiber amplifier and a highly efficient, high power eyesafe fiber laser at 2µm. A common factor in all these systems is the intrinsic high optical conversion efficiency of the fiber gain medium (varying from 55% to 85% depending on the particular system) together with the excellent beam quality intrinsic to the LMA fiber designs with core diameters in the 20-30µm range. As LMA fiber designs and manufacturing mature, some designs are becoming industry standards, which in turn encourage more critical components to be designed as LMA-fiber compatible, further enabling these monolithic platforms to develop into higher power regimes and new wavelengths. Clearly, standard off-the-shelf fiber components are now entering the kWatt power regime.

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