# All-glass Fiber Amplifier Pumped by Ultra-high Brightness Pumps

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**ABSTRACT**

We investigate high brightness pumping of multi-kW fiber amplifier in a bi-directional pumping configuration. Each pump outputs 2 kW in a 200 µm, 0.2 NA multi-mode fiber. Specialty gain fibers, with 17 µm MFD and 5-dB/meter pump absorption, have been developed. The maximum fiber amplifier output power is 2550 W, limited by multi-mode instability, with 90% O-O efficiency and $M^2 < 1.15$. The fiber amplifier linewidth is <12 GHz. We also present kW fiber amplifier results using gain fiber with metalized fiber coating.

**Keywords:** Fiber laser, specialty fiber, pump laser, beam combining, fiber metal coating

## 1. INTRODUCTION

Fiber lasers are efficient, compact devices with excellent beam quality [1-3]. These qualities make them the ideal building blocks for beam-combining applications using both coherent beam combining (CBC) and wavelength beam combining (WBC) techniques [4]. Over the past few years, a number of successful cw beam combining experiments have been performed using kW-class Yb-doped fiber lasers [5,6]. Presently high-power fiber laser combining efficiency over 80% have been demonstrated by multiple groups, and the utility of beam combining to extend cw laser power is well established.

While kW-class Yb-doped cw fiber lasers are inherently nonlinear devices [7], using phase-modulated input to seed these fiber amplifiers can overcome both self-phase modulation (SPM) and stimulated brillouin scattering (SBS). Phase modulation can overcome SPM because the nonlinear phase of phase modulated light represents a constant phase offset and does not affect output optical spectrum or the performance of phase-locked loop (PLL) [5]. In addition, phase modulation broadens the optical spectrum, which can extend SBS power limit.

CBC phase locks the common-mode components of the individual fiber amplifiers. Any higher-order mode (HOM) content in the fiber amplifier output is not combined and represents a loss in combining efficiency. Therefore CBC requires diffraction-limited fiber laser output to achieve good beam combining efficiency. Furthermore, the phase-noise spectrum of the laser output must be within the PLL control bandwidth. For WBC, the bandwidth of the fiber amplifier output needs to be < 15 GHz so the combiner does not cause additional degradation in beam quality. This is in contrast with CBC, whose linewidth requirement is more relaxed as long as fiber dispersion does not cause de-coherence.

A fiber amplifier that is suitable for both forms of beam combining should have both diffraction limited beam and narrow linewidth. Thus far such a fiber amplifier is limited to ~ kW of output. Because COTS pump lasers have limited brightness, the fiber length in a kW fiber amplifier has a lower bound of ~10 meters. Thus to achieve < 15 GHz linewidth at higher output power, a fiber with mode-field diameter (MFD) greater than 20 µm must be employed. Such a fiber can not only contain a sizable HOM content, but also lead to multi-mode instability (MMI) [8-10]. In this paper we examine fiber amplifier performance when pumped by specialty high brightness pumps. These pumps enable efficient pump absorption over a much shorter (3-4 meter) fiber length. Thus multi-kW fiber amplifier with narrow linewidth can be achieved using smaller core fibers.

## 2. EXPERIMENTAL DESIGN

Our fiber amplifier design has three considerations: the pump laser, the active fiber and fiber module thermal management. The pump lasers achieve record pump brightness via WBC technology. The Yb fiber is triple-clad with an F-doped outer-clad for pump guiding. Furthermore, this triple-clad Yb fiber utilizes proprietary waveguide design from

OFS to achieve enhanced HOM suppression to combat MMI. Finally, while the results reported here are obtained using acrylate-coated triple-clad fibers, we are developing triple-clad Yb fiber with gold coating for improved thermal management.

### 2.1 Pump laser

The two pump lasers were procured from Teradiode Inc. and are used to bi-directionally pump the fiber amplifier. Each pump outputs 2 kW in a 200-µm, 0.2 NA delivery fiber. Such record pump brightness is achieved by incorporating WBC technology and represents a 4x improvement over the state-of-art commercial pumps. The E-O efficiency of each pump is ~ 35%. As shown in Fig. 1, in a WBC cavity each emitter operates at a different wavelength and the intra-cavity grating superimposes all the emitters onto a single beam at the output. Thus the output beam brightness can be the same as that of a single emitter [11].

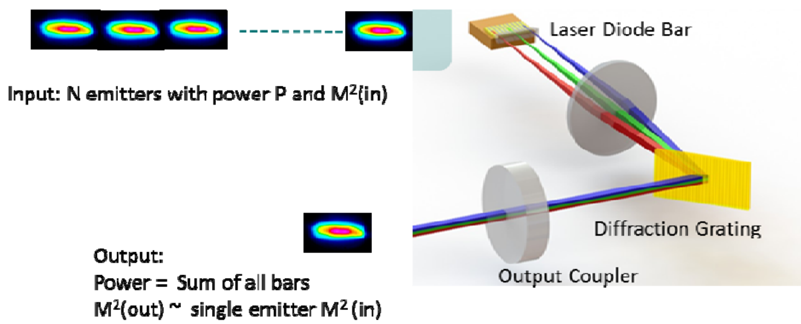


Fig 1. Principle of WBC laser diode bars for fiber laser pumping

### 2.2 Active fiber design

Fiber design balances SBS performance with beam quality and MMI threshold. A fiber with larger MFD can operate at narrower linewidth. However it can also have degraded BQ at the fiber output because of elevated amount of HOM content, as well as a lower MMI threshold. In this work we choose the fiber MFD to be 17 µm. The 20/400 step-index fiber commonly used in fiber amplifiers can have truly Gaussian output while the 25/400 step-index fiber can contain a sizable percentage of HOM energy at high powers. A fiber with 17-µm MFD is comparable to the 20/400 fiber. To match the 200-µm, 0.2 NA pump fibers, the fiber cladding diameter is 180 µm while the F-doped outerclad is designed for 0.24 NA. This leads to pump absorption of ~ 5dB/m at 976 nm. Our design uses 4 meters of active fiber for 20dB total pump absorption so that residual pump does not damage pump lasers. This design translates to ~ 15 GHz of linewidth at 3 kW of fiber amplifier output.

MMI limits diffraction-limited fiber amplifier output power. To combat MMI, we compute the HOM loss for the fiber using its refractive-index profile (RIP). Based on reported work at various organizations [12], we choose >40dB/m HOM loss as the MMI suppression criteria. Because of the high thermal load, we added both dn/dT effects and stress-optic effects to the fiber RIP when computing its HOM loss. Based on these calculations, a 17-µm step-index fiber design cannot support fiber amplifier operation above 2 kW using the high brightness pumps. Instead, we procured active fibers from OFS using their proprietary design [13]. The OFS fibers incorporated a mode-filtering structure for additional HOM loss while maintaining ease of splicing to standard step-index fiber. Fig. 2 shows the calculated performance of one OFS fiber at 0 W and 150 W/m heat load. While the LP11 loss is degraded at 150 W/m heat load, it is still tens of dB/m for a range of coil diameters.

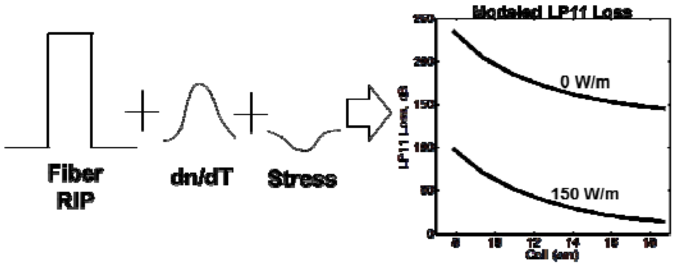


Fig 2. Calculated LP11 loss at 0 W/m and 150 W/m heat load for one OFS fiber.

This specialty fiber design can be used to shift the modal cutoff wavelength below the operating wavelength, thus making the active fiber truly single-mode. A truly single-mode fiber does not allow steady-state propagation of higher-order modes and is often considered as an effective approach to combat MMI. However, further investigation found that because the fiber length in a fiber amplifier is only a few meters, leaky higher-order modes can still propagate in a single-mode fiber amplifier. In fact, a fiber with shorter modal cutoff wavelength can have larger HOM content than a fiber with longer modal cutoff wavelength, as illustrated in Fig. 3. Thus the modal cutoff of the fiber is not a good predictor for MMI threshold. Instead, one must compute the fiber HOM loss to estimate the MMI threshold of the fiber amplifier.

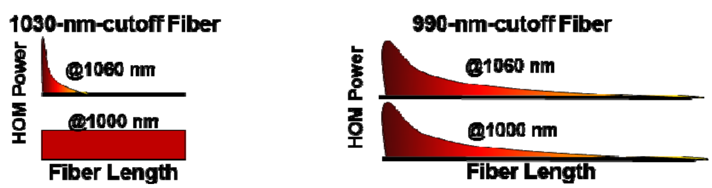


Fig 3. HOM power decay along fiber length for 2 fibers with same 17-µm MFD but different cutoff wavelengths. Different fiber waveguide designs are used to achieve the cutoff wavelengths. The fiber with shorter cutoff wavelength can have slower HOM decay at 1060 nm operating wavelength.

### 2.3 Fiber module thermal management

Because the peak thermal load of our fiber amplifier can be in excess of 150W/m at 3 kW, thermal management of the fiber is of critical importance. Fig. 4 shows the calculated radial temperature profile of the active fiber, assuming perfect heat sinking along its periphery. Even though both inner and outer-clad of the fiber is glass, there is still an acrylate coating outside the glass clad for fiber handling and protection. Calculation shows that the temperature of the fiber acrylate coating can exceed its long-term damage threshold. Such a concern obviously does not apply to a fiber with gold protective coating [14]. Thus in addition to selecting the potting compound for the fiber module, we also have an on-going effort to develop gold-coated gain fiber.

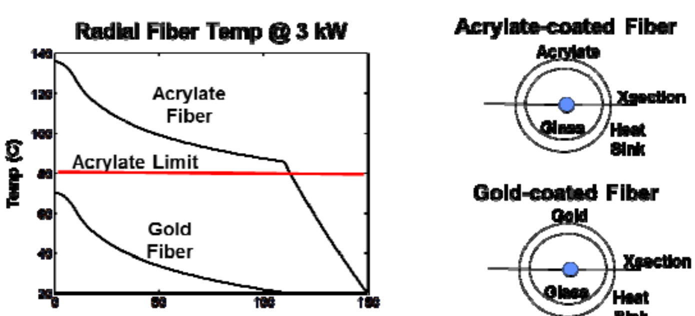


Fig 4. Calculated radial temperature profile of the active fiber, assuming perfect heat sinking along its periphery.

# 3. EXPERIMENTAL SETUP AND RESULTS

## 3.1 Experimental setup

The experimental setup is shown in Fig. 5. The fiber power amplifier is bi-directionally pumped with two 976-nm Teradiode high brightness pumps using dichroic mirrors. The seed wavelength is 1066 nm and is spectrally broadened using an electro-optic phase modulator. The RF drive signal for the phase modulator comes from either a white noise source, or a pseudorandom bit sequence (PRBS) source. The broadened optical seed is then amplified with two IPG pre-amplifiers to achieve output power up to 50 W before it was sent into our fiber amplifier for kW+ output power. The active fiber is potted in an aluminum v-groove plate using thermally conductive RTV (Dow Corning SE4486). The two fiber ends are terminated with 2-mm diameter, 5-mm long fused silica endcaps. The endcaps are AR-coated for both 976 nm and 1066 nm. Both pump and signal are coupled into the active fiber using aspherical single-element fused silica lenses. The fiber amplifier output is coupled out using the counter-pump dichroic mirror and routed into the diagnostics. In addition to power meter, PER measurement, $M^2$ meter, we also use a fiber to measure the on-axis intensity to detect the onset of MMI. While this fiber amplifier does not have a cladding stripper, the cladding light is <30 W. To protect the pump lasers from residual pump power, we design the fiber amplifier length for > 19dB pump absorption. This leads to an O-O efficiency of ~90% for these fiber amplifiers. Furthermore, we found that, while the active fiber is not polarization-maintaining, the fiber modules exhibit large birefringence due to relatively tight fiber coil (12-13 cm) and short fiber length (3-4 meters). The fiber modules have 12-13 dB PER without active polarization control, and their performance is close to the worst-case polarization case. With active polarization control our fiber module PER can be improved to > 18 dB.

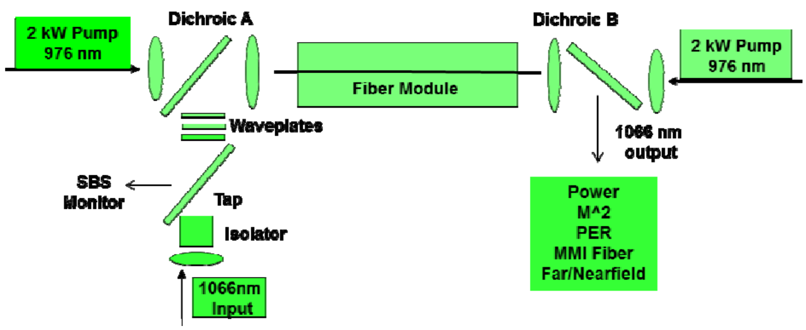


Fig 5. Experimental setup

## 3.2 Experimental results using acrylate-coated Yb triple-clad fiber

The triple-clad active fiber is single-mode at room temperature with a modal cutoff of 1030 nm. Based on HOM loss calculations performed at OFS, HOM loss is >200 dB/m at room temperature but is reduced to 40 dB/m with a heat load of 140 W/meter. This corresponds to the peak heat load for the counter-pumped fiber amplifier case with 1.4 kW of output power. This MMI threshold is confirmed experimentally on multiple fiber modules. The MMI threshold for the co-pump case is similar to the counter-pump case. The MMI threshold nearly doubles with bi-directional pumping, to 2.6 kW. This is because bi-directional pumping reduces both dn/dT and $\Delta T$ by ~ a factor of 2 at fixed output power compared with single-side pumping. Fig. 6a shows the experimental data including co-pumping, counter-pumping and bi-directional pumping cases. The O-O efficiencies for all three cases are 90%. The $M^2$ for all the cases is < 1.15 up to 2.5 kW of output power. Fig. 6b shows the OSA spectrum containing both backward Raleigh and SBS signals at 2.1 kW. With a 10 GHz PRBS-8 signal, the SBS signal is still below the Raleigh backscatter. We used 12 GHz PRBS-8 input to seed the 2.5 kW fiber amplifier output.

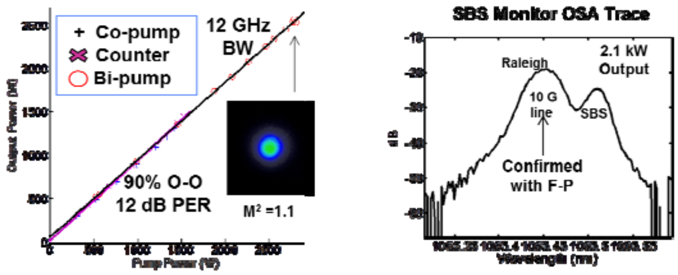


Fig 6. Experimental results using acrylate-coated Yb triple-clad fiber (a) Pump vs. output for co-pumping, counter-pumping and bi-directional pumping (b) Backward Raleigh scattering and SBS at 2.1 kW

### 3.3 Experimental results using gold-coated Yb triple-clad fiber

This triple-clad active fiber is single-mode at room temperature with a modal cutoff of 990 nm. Even though this fiber has shorter cutoff wavelength, its HOM loss is significantly less than the fiber reported in Section 3.2 because of the waveguide design. We applied both acrylate coating and gold coating on this fiber waveguide. For both types of coating, we found the MMI threshold for the counter-pump case to be <700 W. With bi-directional pumping we achieved 1.2 kW before encountering MMI. Fig. 7 shows the pump vs. output curves for the gold-coated fiber. The efficiency is 90% and $M^2$ is < 1.15. While the fiber amplifier power is limited by MMI, this work shows that active fiber with gold coating can achieve kW output power without any degradation in O-O efficiency or beam quality.

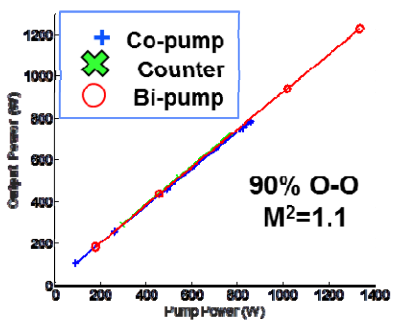


Fig 7. Pump power vs. output power for gold-coated active fiber

## 4. CONCLUSION

We investigated a fiber amplifier using a short active fiber pumped by ultra-high brightness pumps, and achieved a beam-combinable 2.5+ kW linearly-polarized fiber amplifier with 90% O-O efficiency and 12 GHz linewidth. This achievement is enabled by record brightness pumps and large-mode-area single-mode fiber. We also present a successful demonstration of gold-coated kW fiber amplifier. This investigation gained better understanding of MMI in single-mode fiber. This improved understanding can lead to new fiber design with enhanced MMI suppression. Finally, we believe that current COTS fiber amplifier performance can be significantly improved by using brighter pump lasers

## 5. ACKNOWLEDGMENTS

We would like to thank Thierry Taunay and Brian Mangan at OFS for fiber design and fabrication. We would also like to acknowledge Mike Cruz and Robin Huang for furnishing the high brightness pump lasers.

This work is sponsored by DARPA under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

## REFERENCES

[1] Khitrov, V., Minelly J., Tumminelli, R., Petit, V., Pooler E. S., “3kW single-mode direct diode-pumped fiber laser,” Proc. SPIE 8961, 896120V(2014).

[2] Huang, Y., Edgecumbe, J., Ding J., Holten, R., Ahmadi P., Wang C., Guintrand C., Farley, K., Christensen S., Tankala, K., "Performance of kW class fiber amplifiers spanning a broad range of wavelengths: 1028~1100nm" Proc. SPIE 8961, 89612K (2014).

[3] Rosales-Garcia A., Tobioka H., Abedin, K., Dong, H., Várallyay, Z., Szabo, A., Taunay, T., Sullivan, S., Headley, C., “2.1 kW single mode continuous wave monolithic fiber laser” Proc. SPIE 9344, 93441G (2015).

[4] Yu, C. X. and Fan, T. Y., [High-power laser handbook], The McGraw-Hill Companies, New York, 533-571 (2011).

[5] Yu, C. X., Augst, S., Redmond, S. M., Goldizen, K., Murphy, D., Sanchez, A. and Fan, T. Y., "Coherent combining of a 4 kW, eight-element fiber amplifier array," Opt. Lett., 36(14), 2686 (2011).

[6] Goodno, G., McNaught, S., Rothenberg, J. E., McComb, T., Thielen, P., Wickham, M. and Weber, M. E., "Active phase and polarization locking of a 1.4 kW fiber amplifier," Opt. Lett., 35(10), 1542 (2010).

[7] Agrawal, G.P., [Nonlinear fiber optics], Academic Press, San Diego, (1995).

[8] Ward, B., Robin, C., and Dajani, I., “Origin of thermal modal instability in large mode area fiber amplifiers,” Opt. Exp., 20(10), 11407 (2012).

[9] Smith, A., and Smith, J., “Mode Instability in high power fiber amplifiers,” Opt. Exp., 19(11), 10180 (2011).

[10] Karow, M., Tünnermann H., Neumann J., Kracht D., and Webels, P., "Beam quality degradation of a single-frequency Yb-doped photonic crystal fiber amplifier with low mode instability threshold power," Opt. Lett., 37(20), 4242 (2012).

[11] Chann, B., Goyal, A., Sanchez, A., Fan, T. Y., Volodin, B., and Ban, V., "Efficient, high-brightness wavelength-beam-combined commercial off-the-shelf diode stacks achieved by use of a wavelength-chirped volume Bragg grating," Opt. Lett., 31(9), 1253 (2006).

[12] OFS, private conversation; Nufern, private conversation.

[13] Taunay, T., “Gain-producing fibers with increased cladding absorption while maintaining single-mode operation,” patent pending.

[14] Delcher, R., “Fiber optic characteristics for extreme operating environments,” NASA report CR189189 (1992).