High power monolithically integrated all-fiber laser design using single-chip multimode pumps for high reliability operation

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ABSTRACT

We present an all-fiber monolithically integrated fiber laser based on a custom tapered fused bundle pump combiner with 32 inputs ports connected to a double clad gain fiber. The pump combiner is designed to provide high isolation between signal and pumps fibers providing intrinsic pump protection. This configuration can generate more than 100W of continuous wave (CW) laser light using single-chip multimode pumps enabling long term reliability.

Keywords: Fiber laser, High power, tapered fused bundle, single emitter pumps

1. INTRODUCTION

High power fiber lasers and amplifiers are now reaching the manufacturing and commercialization phase [1-2]. As such, fiber laser configurations require robust designs to go beyond prototype demonstration. Replacing bulk optic elements by all-fiber components for the functions of mode field adaptation, laser light reflection, output coupling as well as pump and signal combination will increase the stability, long term reliability and robustness of fiber lasers [3-4-5]. A continuous waveguide also eliminates issues related to alignment and vibration sensitivity. We propose a new all-fiber laser design using all-fiber components and a 32 input ports tapered fused bundle (TFB) monolithically integrated to a double clad (DCF) output ytterbium (Yb) doped gain fiber. The laser is designed to optimize manufacturability, simplicity and high reliability for real life applications rather than state of the art performance.

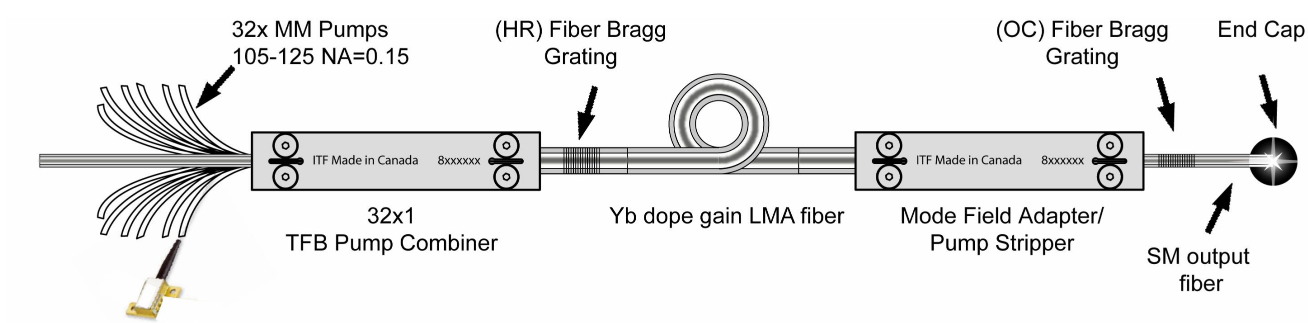

Fig. 1. Fiber laser design. An all-fiber 32x1 TFB is spliced to a 20-400 Yb dope DCF gain fiber. Bragg gratings act as high reflector (HR) and output couplers (OC). 32 passively cool multimode single emitter pumps are used. An output mode field adapter ensures single mode operation. An all-fiber end cap at the laser output allows beam expansion for safe beam delivery.

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2. FIBER LASER TOPOLOGY AND DESIGN

2.1 Pumps configuration

A Schematic of our fiber laser is illustrated in Fig. 1. 32 multimode pumps are spliced to a 32x1 TFB allowing end pump coupling in the cladding of a 20-400 Yb doped DCF gain fiber with more than 200 W of pump light at 915nm (7W per pump). Single emitter of 7W output at 915nm pumps were chosen to avoid expensive water cool bar and more complex temperature control scheme required when using 976nm pumps event if the wall plug efficiency of the laser is reduce and if the gain fiber length require. Since the absorption spectrum of the Yb dope gain fiber is very large around 915nm, this feature enables the use of air cool 915nm multimode pumps. We believe that a complete air cool system avoiding cumbersome water cooling system is a great advantage and cost saving for laser in the 100-200W output power range. We also think that using single emitter enhances the overall reliability of the system. MTBF (mean time before failure) is higher on single emitter than on a bar stack and with 32 ports. We can think of designing a system with margin to accept failure of 1 or 2 pumps since each pump asses for 1/32 of the total pump power. Of course single emitter pumps are more fragile to back-reflected signal and pumps light. The following section address this issue of reliability with a unique high isolation TFB. Fig 2. shows the 32 singles emitters pumps air cooled and operating at 915nm.

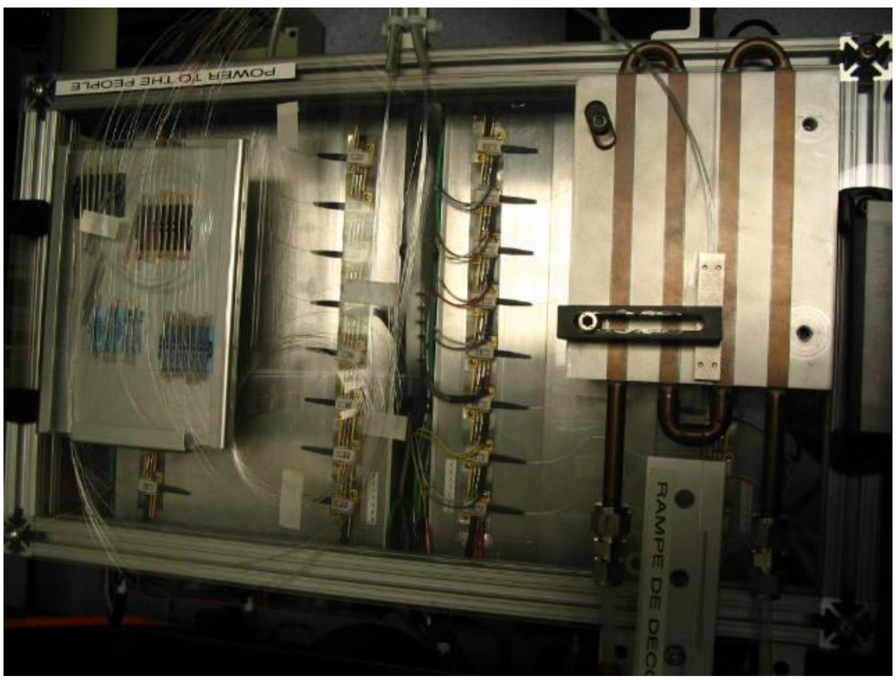

Fig. 2. 32 Pump mounted on a 12 inch rack mount air cool prototype enclosure going into a 32+1x1 custom TFB to deliver 200W of pump power in a 20-400 double clad fiber. The TFB in mounted on a watercool plate for testing purpose. The final system is expected to run completely air cool.

2.2 Tapered fused bundle (TFB) design

The TFB is designed and fabricated to provide high pump to signal isolation for pump diode protection purposes. The TFB construction is illustrated in Fig. 3. The 32 pump fibers are distributed around a central fiber. We are intentionally using the largest fiber possible in the middle to guides the ASE light as well as a large amount of unwanted back reflected signal light out of the laser without affecting the pumps. However, this technique reduces the brightness efficiency of the pumping scheme, but we are still ending with 32 ports coupled to a widely use 400um cladding DCF fiber. An extension of our work will be to provide the center fiber of the 32x1 TFB with a core for integrated laser signal monitoring. For now, we can sample the highly multimode light coming out of the dump fiber; spectrums are shown in the experimental results section.

The measured pump loss and isolation is illustrated on fig. 4 and 5. Average pump loss is only 7.2% and the pump isolation is more than 21 dB on all ports. The isolation measurement is done with a fully filled (at NA=0.46) multimode pigtailed source spliced to the output of the 32x1 and light is back-propagated towards the pump ports. A fully filled source means that the brightness of the source is kept constant for all guided rays. All guided rays transmit the same amount of light as in a Lambertian source. It is important to point out that this test procedure will be the worst case scenario for a TFB in a laser configuration.

The high power TFB package has been previously qualified for high power handling and demonstrated to handle kW level powers [7]. Using a thermal camera we have monitored the combiner when 210W of pump power is injected in the component. The TFB was sitting on a actively cooled base plate and the hottest point was measure to be 38°C. This was mainly due to the 4% back reflected light from the end cleave of the combiner since no active fiber was attach for this test. In the laser configuration, the TFB was running at 26°C. We believe that this TFB could easily be operated at full power in an air cooled system.

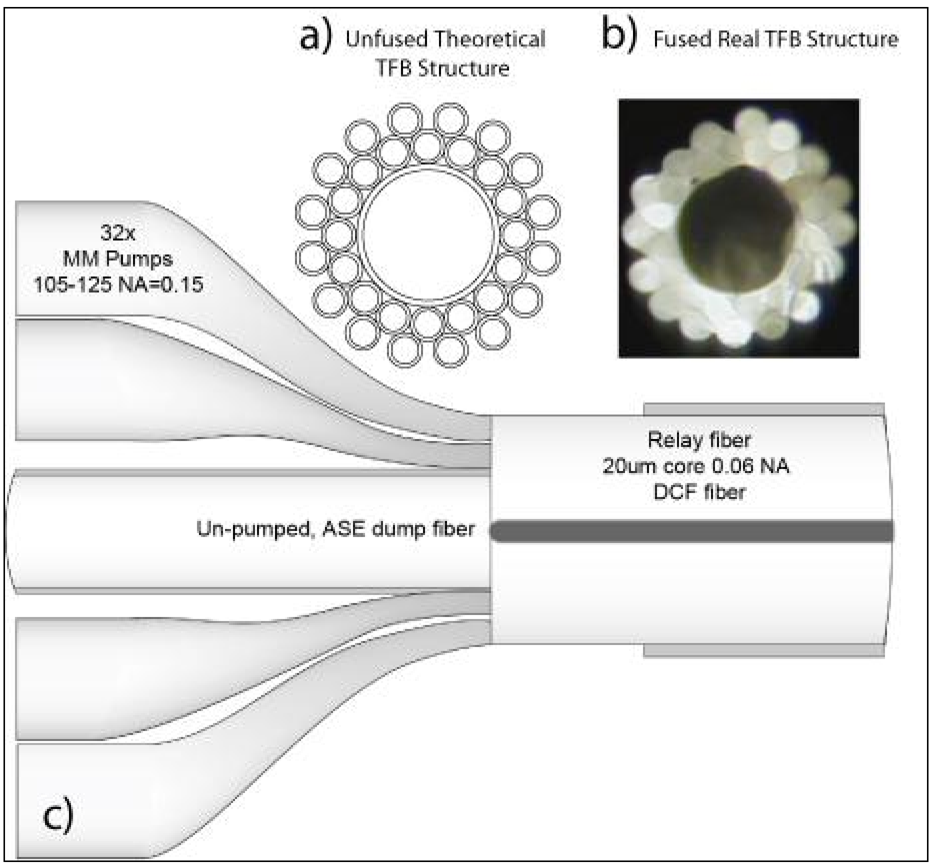

Fig. 3. 32x1 TFB design providing high pump isolation. The 32 surrounding fibers are 105-125 0.15NA pump fibers. The final structure is fused and tapered to match an output relay fiber with an output diameter of 400um. a) unfused theoretical structure b) real structure before fusion with output fiber c) theoretical final structure

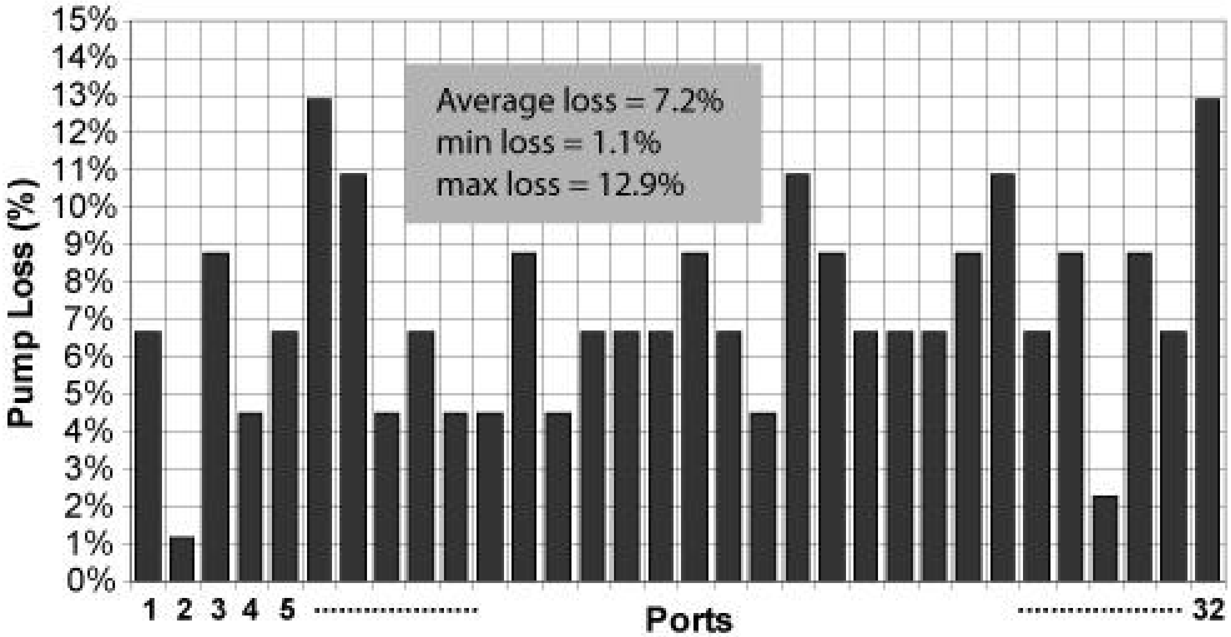

Fig. 4. TFB pump loss over 32 ports. Average loss is 7.2%.

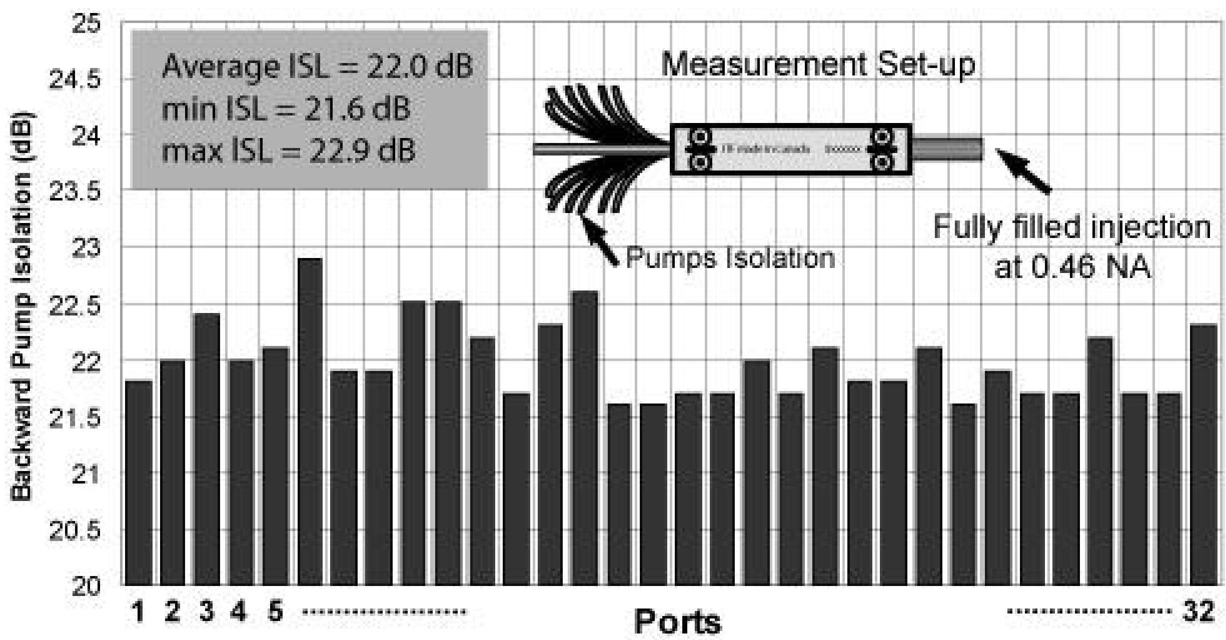

Fig. 5. Pump isolation results when fully filled source are injected at the output of the combiner simulating the worst case scenario of unwanted back propagating light.

2.3 High reflector Bragg gratings

The high reflector (99%) is a Bragg grating inscribe in a relay undoped 20-400um DCF fiber spliced to the output of the TFB and before the gain fiber. Since 200W of pump light need to be guided in the cladding surrounding the core where the Bragg grating is written, packaging and thermal management need careful attention. Small amount of pump loss in the coating can heat locally the Bragg gratting. To avoid thermal laser line instability, we use a large 3nm bandwith Bragg gratting as a high reflector. Since the 20-400um DCF fiber is slightly multimode around 1080, we use mode field adaptors for single mode measurement and fundamental mode reflection optimization during the bragg grating fabrication process (see test setup on figure 6.). The high reflector transmission and reflection spectrums are presented in fig 7.

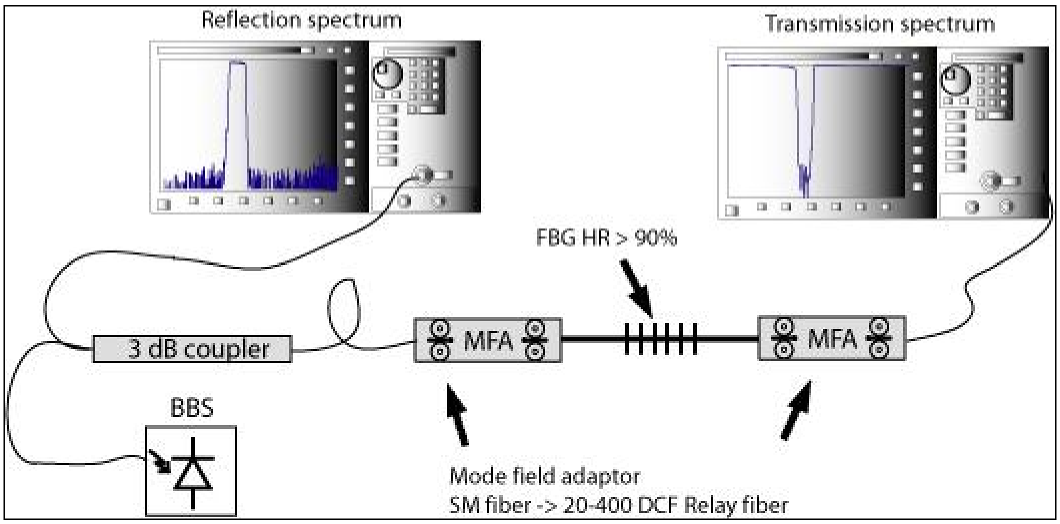

Fig. 6. The Bragg gratings written in DCF 20-400 fiber are measure in transmission and reflection between 2 mode field adaptor for single mode spectrum characterization and fabrication optimization.

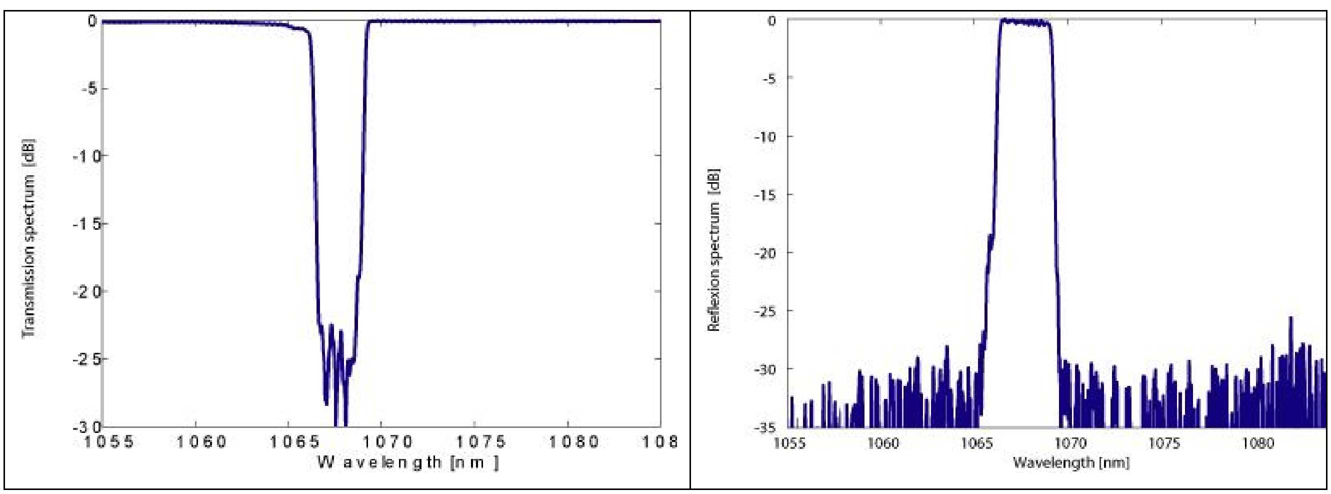

Fig. 7. Fiber Bragg grating high reflector transmission and reflection spectrum

2.4 Pumps stripper and mode field adaptor

For stable single mode operation of the laser and for diffraction limited beam quality ($M^2 \approx 1$), an output MFA[6] is designed to transmit the fundamental mode of the 20um core few moded laser fiber to the single mode 10um 0.08NA output fiber an filter out unwanted high order core mode. This MFA is also packaged with a new cladding light stripper component develop by ITF this year [8]. This component acts as a residual cladding light stripper in both directions.

2.5 Output coupler

This all-fiber configuration uses another fiber Bragg gratings (FBG) for laser output coupler (OC). The OC Bragg grating is written in a single mode fiber after the MFA. This strategy avoids feedback of any other mode in the 20-400um fiber. Gain coiling is not needed in this configuration. The output coupler reflectivity is presented with the laser output spectrum on fig. 10 in the results section.

2.6 Laser termination (End Cap)

In our design, an ITF end cap enables the core light to expand and decrease the power density at the output of the laser for safe beam delivery. Fig. 7 shows the air damage threshold limit for CW light in an optical fiber against mode field diameter. This curve is base on a theoretical value of $10W/um^2$. We use a 10x safety factor on this maximum power to establish a safety limit for long term operation. For a 10um 0.08NA single mode delivery fiber, the end cap is not mandatory around 150W of output power but reducing power density prevents dust attraction from the high intensity electrical field at the end facet. Since the end cap length is fixed, the divergence of the beam is higher for small MFD creating a bigger beam size at the end cap end and increasing the maximum power before reaching the air damage limit. This explains why the end cap maximum power handling decreased when you increase your MFD. However the actual design will be limited by the packaging power handling well before reaching the limit show on this graph.

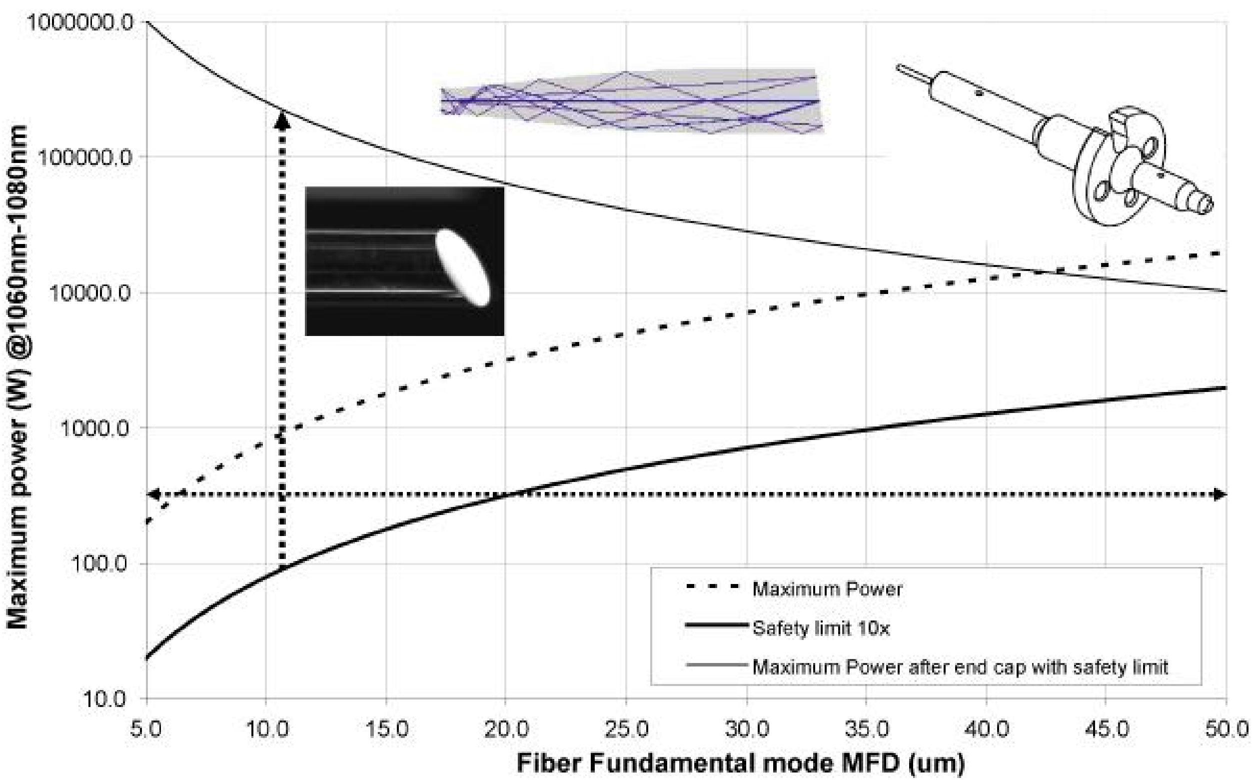

Fig. 8. Air damage threshold curve with safety factor vs mode field diameter of laser output fiber explain beam expansion requirement on high power laser. Insert picture shows images of the polish angle end facet of an end cap with ray tracing analysis on back traveling light and the actual mechanical drawing of the end cap.

3. LASER EXPERIMENTALS RESULTS

In this section, we present preliminary results of the configuration that we have described earlier. Overall, the optical laser efficiency including the TFB loss is 46%. If we normalize for the loss of the TFB (7% in average), the relay to gain fiber splices loss (2x) and the mode field adaptor loss, the lasers have an efficiency over 70%. This clearly indicates that the system designer needs to optimize simple aspects such as splice loss between the relay and gain fiber to improve all-fiber efficiency.

Fig 9 show the effect of our pump stripper at the output of the laser. It's also show how well we could use the ASE beam dump fiber of our 32x1 TFB to monitor the system performance. On fig. 10, the spectrum at the output of the system is compares to the output coupler spectrum showing an effective narrowing of the spectrum confirming that our feedback is appropriate for the laser.

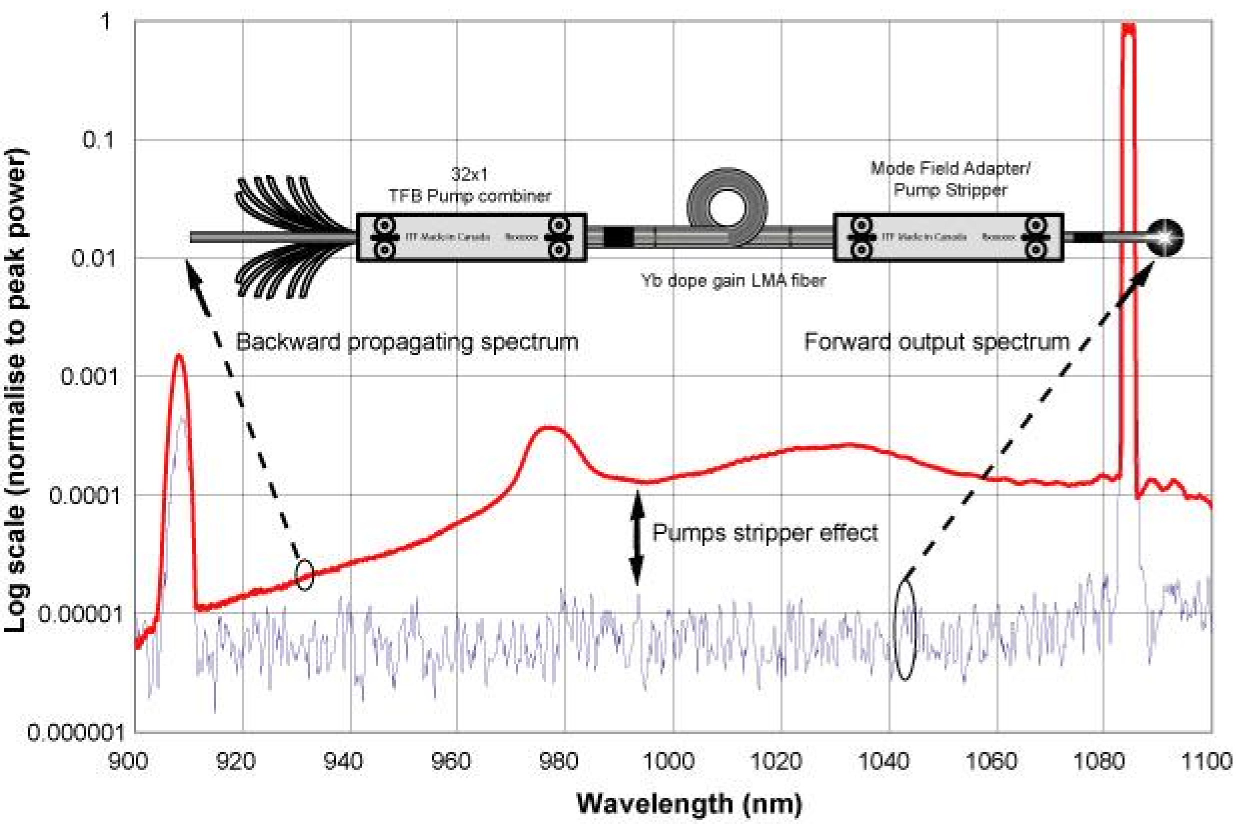

Fig. 9. Spectrum of the laser output on a large wavelength range compare to the backward spectrum measure from the dump fiber (see figure 3.) The effect of the cladding light stripper is clearly visible between the 2 curves.

The single mode delivery fiber length needs to be keept short (<1m) to avoid non-linear effect. For CW system, the first non-linear effect to be trigger will be the stimulated brillouin scattering (SBS). But fortunately, the MFA and the output coupler bragg gratting chirp limit the acoustic wave transmission and the phase matching between the 20-400 and the single mode delivery fiber reducing the effective length of the system regarding the SBS threshold.

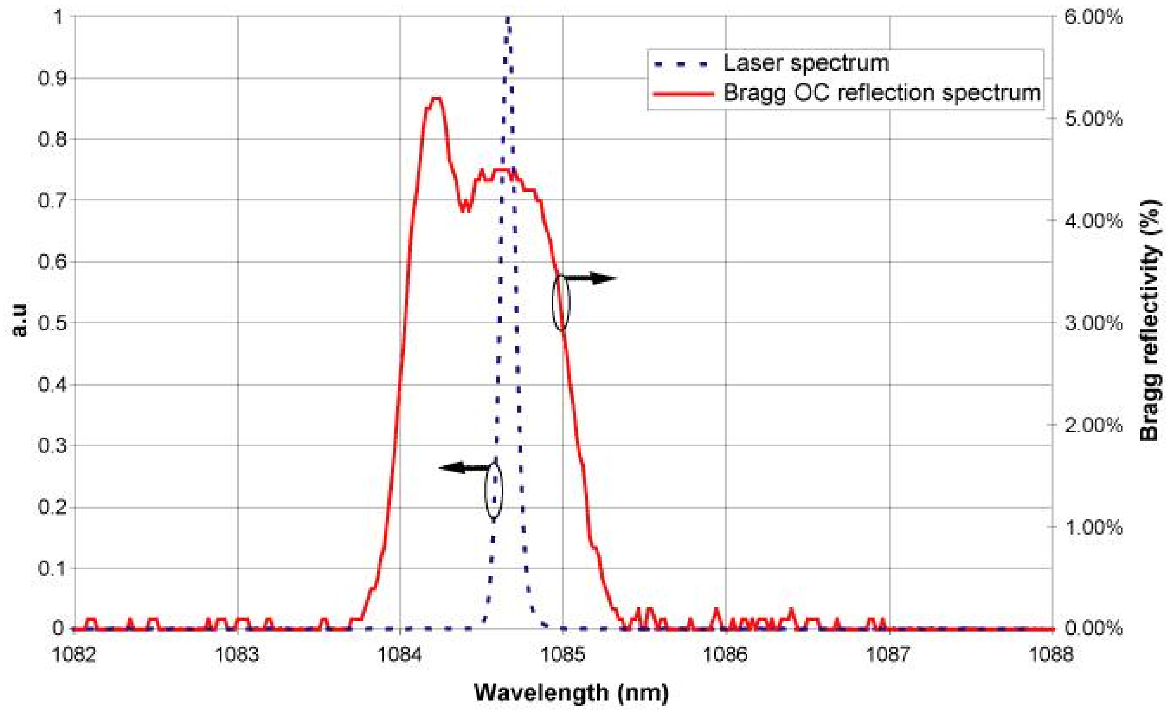

Fig. 10. Laser spectrum (dot curve) and Bragg grating output coupler reflectivity spectrum (plain curve)

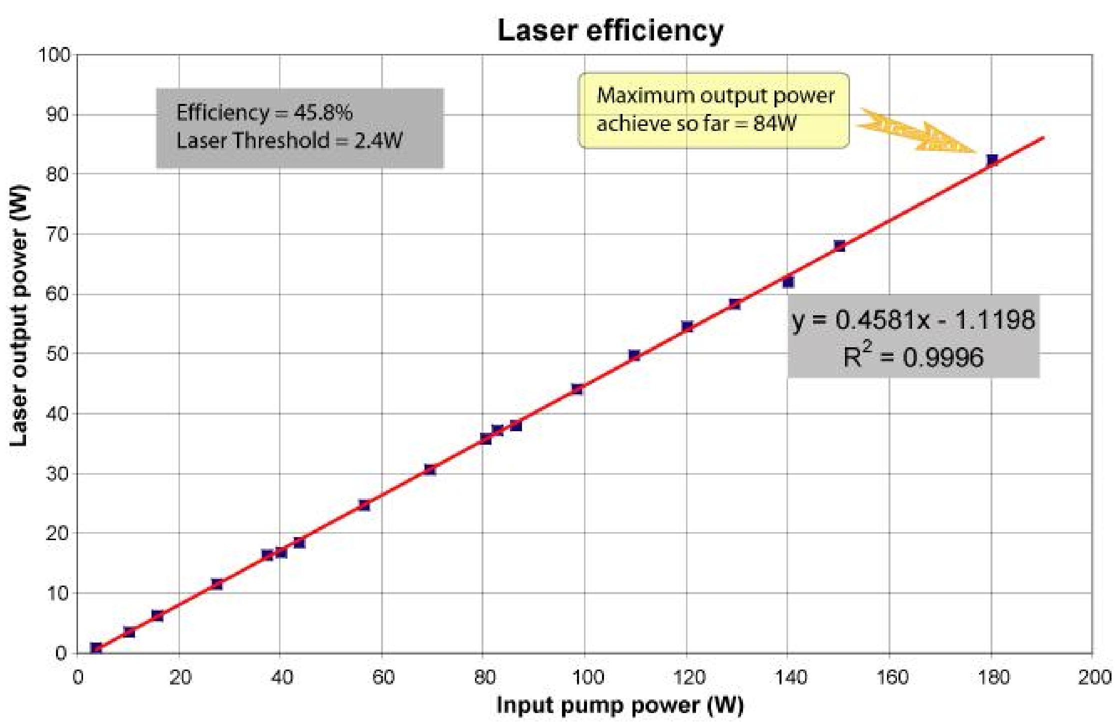

Fig. 11. Laser efficiency including TFB and MFA losses.

4. CONCLUSION

We have presented an all-fiber laser design using only all-fiber components. The laser was designed to optimize manufacturability and high reliability. A new high isolation and high count ports (32) TFB was specifically developed for this application enabling the use of low cost single-chip multimode pumps. Demonstration of Bragg grating and pump stripper operation at high power has been completed. The configuration can generate more than 100W of continuous wave (CW) laser light. 84W have been demonstrated so far.

The overall laser efficiency still needs to be improved and we believe that integrated optical engines eliminating as many splices as possible will have to be developed. Integration of gain fiber inside TFB and MFA as well as Bragg grating on gain fiber should be envisioned.

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