Component Testing and Amplifier Design for 200W, Narrow Linewidth, Monolithic PM-LMA Fiber Amplifiers

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ABSTRACT

Directed energy weapons systems operating in the 100kWatt regime will most likely combine the outputs of multiple lower power fiber lasers and/or fiber amplifier "building blocks.".. Combining techniques, for example, coherent and spectral beam-combining, are currently the topic of much research. Many of the combining techniques being considered impose similar critical requirements on the basic fiber laser building block, namely, narrow linewidth (long coherence length), linearly polarized output and single mode beam quality. In addition, the fiber building block should have as high an output power as possible in order to minimize the number of units required to scale towards 100kW. Finally, the overall design of the directed energy device should be monolithic, that is, a single continuous fiber chain, without free-space optics.

The components to build a monolithic polarization-maintaining (PM) fiber amplifier in the 200W regime are only now becoming available. In this paper we will report the testing of the critical components such as high brightness pump diodes, fiber couplers/combiners along with the associated fibers, typically in the 300W pump power regime. Key parameters such as pump and signal insertion loss, PER and thermal loading will be reported in detail.

In addition, the effect of amplifier design on the critical requirements noted above will be discussed, including the advantages of co- and counter pumped amplifier designs and the number of amplifier stages required to reach the 200W output power target using commercially available, narrow linewidth seed laser sources. We will report experimental results on a narrow linewidth, monolithic PM-amplifier chain operating in the 200W regime and the prospect for future power scaling.

INTRODUCTION

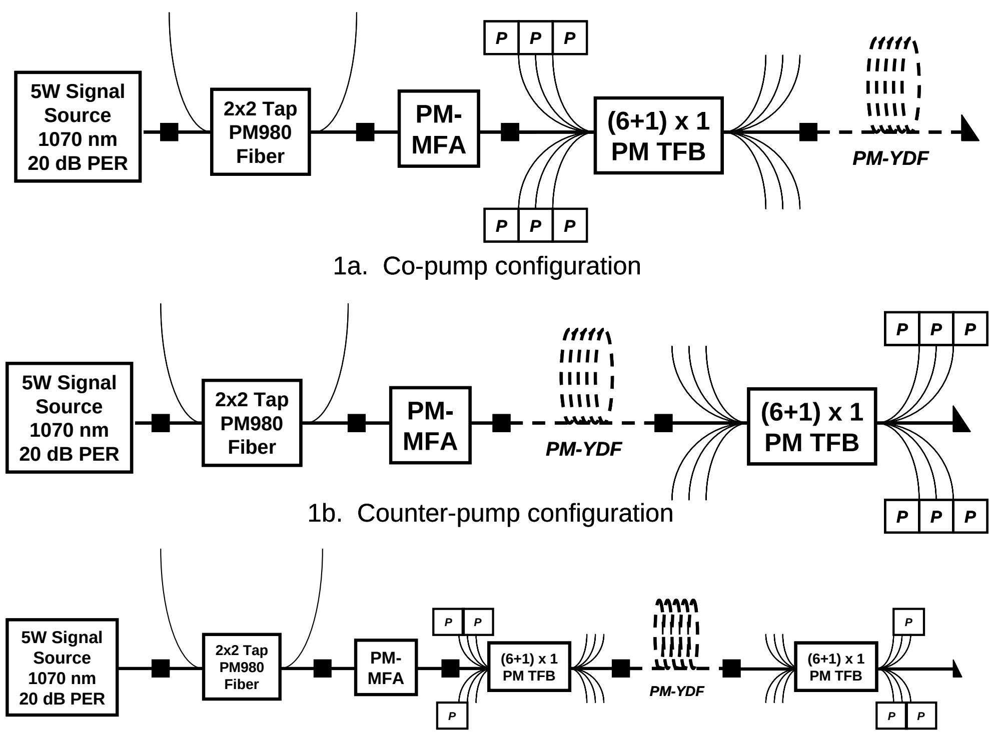
High-power fiber amplifiers represent one path to efficiently achieve 100kW-range output power sources. They are well suited for amplifying the polarized, narrow linewidth seed signals required for high power combining techniques and hence have attracted a great deal of interest. A monolithic (i.e. all fiber) device is preferred for such an amplifier, as there are no free-space optics to align nor a multitude of surfaces to protect from the high intensity powers created by such a device. If the use of free space optics is not entirely avoided, the use of such optics can at least be limited. A monolithic fiber amplifier will be more reliable in the field.

The success of building a high-power amplifier relies much on the quality and performance of its components.. This is especially true for a polarization maintaining (PM) amplifier, as the technology required to maintain signal polarization at these powers is more involved. Reliably coupling pump power into an all-fiber high-power amplifier remains a challenge.. Tapered Fiber Bundle (TFB) technology currently shows the greatest promise for coupling the pump power while maintaining the lengths of the active/passive fiber as relatively short. This is especially true with improvements in the technology for PM TFB devices[1]. Pump diodes having increased output brightness are obviously advantageous for pump coupling, and vendors continue to introduce higher output brightness diodes. Utilizing smaller-core fibers to deliver high pump-powers is very much in line with the pump-fiber sizes required by TFBs to operate with the current large mode field (LMA) fiber technology[2]. LMA fibers, in themselves, have been very successful over the years with > 1kW output powers demonstrated[3] for non-polarized light and > 400W for polarized light[4] in free-spaced experiment efforts. A non-PM, high power monolithic amplifier emitting 200W, presented recently, further demonstrates the capability of the TFB and LMA fiber technology[5].

In this paper we discuss the design, fabrication and characterization of a > 200W monolithic fiber device capable of polarization-maintained amplified output. We include data on individual component characterization, as some of these components have only been recently available, as well as the performance of the amplifier in different configurations (co-pump, counter-pump and bi-directional pumping). Future work will also be discussed in investigating amplifier performance with input signal linewidths approaching 10s of kHz.

PROCEDURE AND AMPLIFIER DESIGNS

Figure 1 illustrates the tested amplifier designs – co-pumped, counter-pumped and bi-directionally pumped configurations. In each configuration, a 5W PM 1070 nm laser source with 20 dB PER (IPG Photonics) was used as an input signal (~ 0.8 nm linewidth). A 0.1% tap coupler (SIFAM Fiber Optics) followed in order to (a) monitor the amount of signal power entering the PM-MFA/amplifier section, and (b) monitor the amount of backwards-traveling power to avoid damaging the source. The PM-MFA (ITF Optical Technologies), directly following the tap coupler, was used to preserve the Gaussian mode field within the 6 micron single-mode fiber when injected into the 20 micron, 0.06 core NA passive fiber. The PM-TFB (ITF Optical Technologies) utilizes pump delivery fibers (200/220 micron, 0.22 NA core) and a Nufern PLMA-GDF-20/400 as the double-clad signal input/output fiber. This PM-TFB, although having 12 pump fibers, is actually a (6+1) x 1 type combiner, where six fiber legs transmit the coupled pump power and the remaining six fiber legs help remove un-coupled pump power (i.e. pump power that does not make it to the PLMA-GDF-20/400 fiber) from the package so the heat load on the package is reduced. The design of the PM-TFB is such that the polarization properties of the double clad fiber are minimally affected and the signal insertion loss is near zero. The latter fact allows the device to be used in the counter-pump and bi-directional pump configuration, where previous versions of TFB devices (by any vendor) often exhibited higher signal insertion losses when signal light transmitted in an opposite direction to pump light. This design, however, does introduce more pump loss than the non-PM TFB version. For the bi-directionally pumped configuration, two PM-TFBs were used. The active fiber, PLMA-YDF-20/400 (Nufern), is a Ytterbium (Yb^{3+})-doped PM double clad fiber with ~ 13 dB absorption at the pump wavelength. This fiber was coiled within a standard Nufern cooling coil used to (a) remove heat from the fiber during amplifier operation and (b) to provide diffraction limited operation, as the fiber is inherently 2-moded at 1070 nm[6]. The pump diodes used produced 50W each at 976 nm (LIMO) and are represented in Figure 1 by a boxed “P”. For every configuration, an angled end cap was used to terminate the double clad fiber in order to (a) reduce back reflections at the fiber output and (b) reduce the output signal intensity at the fiber face to lower the risk of damage. Characterization of parts included the PLMA-YDF-20/400 fiber, the PM-MFA (IL, PER) and PM-TFB (IL, PER). A high power, PM single mode isolator was to be used between the signal source and 2x2 tap coupler, but was unavailable at the time of testing. However, since the signal source had its own isolation and the amplifier tests for each configuration did not produce much backwards-traveling power, all tests could be performed under a fully computer-controlled system that monitored all power readings. During amplifier operation, all components were water cooled to maintain a suitable operation temperature.



1a. Co-pump configuration

1b. Counter-pump configuration

1c. Bi-directional pump configuration

Figure 1 – Amplifier Configurations

RESULTS AND DISCUSSION

Figure 2 shows fiber characteristics and the slope efficiency of the PLMA-YDF-20/400 fiber as a laser with Fresnel reflectors on both ends. Approximately 86% conversion efficiency was observed with the 169 W of pump power available for this test.

Testing of the LIMO pumps showed each pump capable of near 50 W output, with center wavelengths near 978 nm at 50W power (drive current 45A). The total pump power available for the tests was ~ 314W at 45A.

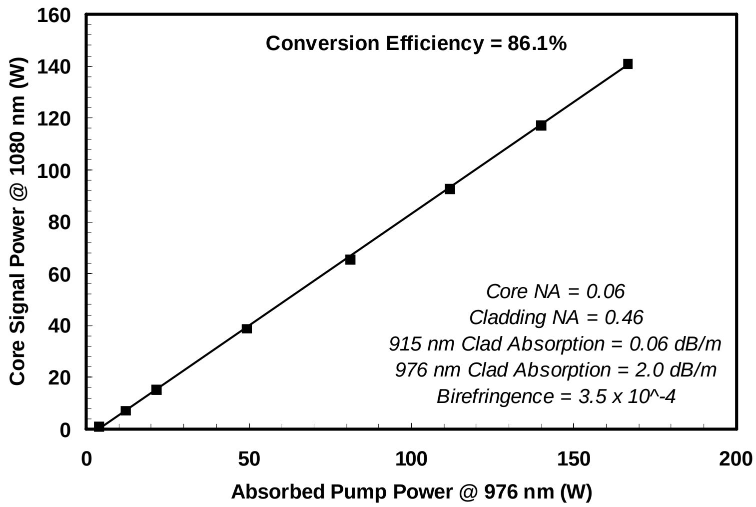


Figure 2 – PLMA Fiber Characterization

Table 1 summarizes data measured on the PM-MFA and PM-TFB. Two devices of each were characterized. For the PM-MFAs, the insertion losses were 0.22 dB and 0.51 dB at 1070 nm and the PER values were 12.5 dB and 17.6 dB. All values were measured with ~ 3.5 W signal power (maximum power handling < 15 dB for each device). For the TFBs, each was capable of handling over 300W coupled pump power (with active cooling) by providing over 275W output. The extra pump fibers were found to guide ~ 9W of uncoupled pump light away from the package (~ 31% of wattage lost due to the PM-TFB). The signal PER for one of the devices, measured using 3W of 1070 nm input signal with and without the pump power on (no YDF spliced), gave the same 16 dB PER, indicating that the pump power injected did not affect the PER of the device. Although the average insertion losses (ILs) were 0.49 dB and 0.58 dB (the latter loss is larger due to an outlier), the most interesting behavior of the PM-TFBs was the change in insertion loss with pump power, as seen in

MFA (ID#)	Input Fiber Type	Output Fiber Type	1070 nm Insertion Loss (dB)	1070 nm PER (dB)
8005587	PM980-HP	PLMA-GDF-20/400	0.51	12.5
8005588	PM980-HP	PLMA-GDF-20/400	0.22	17.6

(a) PM-MFA Data

Pump TFB ID #	Input Fiber Type	Output Fiber Type	Pump Input Power (W)	Pump Output Power (W)	Average Pump Insertion Loss (dB)	Average Signal PER No Pump Power (dB)	Average Signal PER With Pump Power (dB)	Exit Port Pump Power (W)
8005584	200/220, 0.22 NA	20/400, 0.06/0.46 NA	306.2	276	0.49	-	-	9.37
8005586	200/220, 0.22 NA	20/400, 0.06/0.46 NA	305.5	279	0.58	16.07	16.03	8.72

(b) PM TFB Data

Table 1 – (a) PM-MFA and (b) PM-TFB Data

Figure 3. The change in IL is favorable, as with increasing output power the insertion loss approaches 0.4 dB (or 90% transmission efficiency) at full pump power. The exact mechanism behind this loss change is still under investigation.

These results do show that the latest PM-TFB component works very well and may be able to handle higher powers than injected in this study.

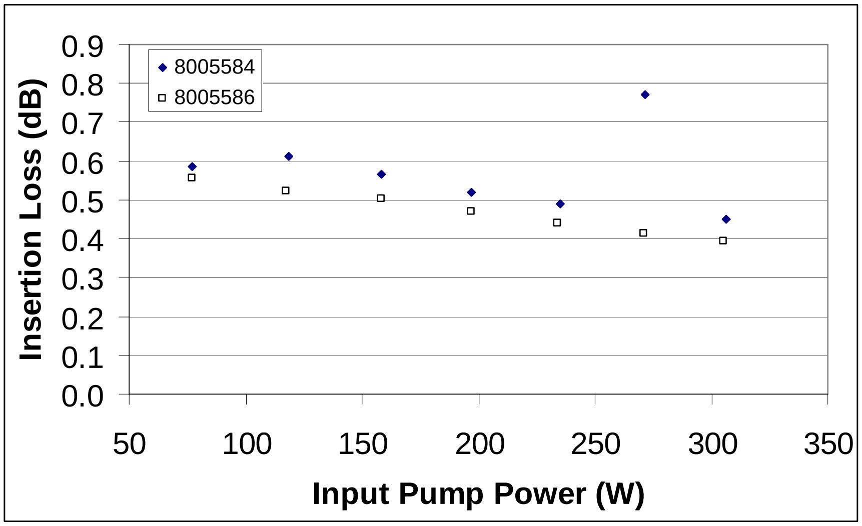


Figure 3 – PM-TFB Combiner Insertion Loss Change with Increasing Pump Power

Table 2 summarizes the amplified signal characteristics for each amplifier pump configuration. For all configurations, output powers of 220W or greater were achieved (coupled pump power to the YDF fiber ~ 279W). Only a pump blocking dichroic filter was placed between the water cooled thermopile detector (Ophir Optoelectronics) and the amplifier output. The conversion efficiencies were over 85%, and the output power PERs averaged about 16.5 dB (PER values were measured after consecutive increases in pump diode drive current). Given that the input signal itself had 20 dB, and the PER of the MFAs measured were also near 15 dB, indicates that only slight differences measurements, set up, splices, etc. could be the cause of the differences in PER and that, with a higher PER signal source, the PER of the amplifier indeed may be higher than measured. The amplifier gain, nearly 17 dB, provided output spectra with near 40 dB signal to noise ratio. For all three designs, the signal within the cladding of the output double clad fiber was ~ 1%. Although not directly measured, the beam quality of the amplifier output appears Gaussian and given the nature of the coiling technique used, along with the fiber geometry, the expected M^2 value is between 1.1 - 1.2. These impressive results further demonstrate that monolithic fiber devices can achieve high power performance and operate to maintain the polarization of the input signal. What is equally important is that these devices, using 976 nm pumping, are providing extremely high conversion efficiencies (the theoretical efficiency is just slightly higher than 91% for the pump and signal used). It is noted, however, that during the counter-pump configuration testing, there was a drop in output power by about 4% during the experiment (the 4% drop was observed, compared to the initial measured output power, when the system was restarted after a power-drop related system shutdown). This power drop may indicate that exposing these newly developed PM-TFBs to both high power pump and signal, simultaneously, may cause some type of damage within the unit (in this case, the unit was still used for many hours afterward). Without this 4% drop, the counter-pump and bi-directionally pump cases would have emitted very similar output powers (230W) compared to the co-pump case (222W), an efficiency difference to be expected. The co-pump configuration, however, provided very impressive results and has its advantages over the other two systems. It is less costly than the bi-directional system, given that only one PM-TFB is required, and at present, does not have the reliability risk that the counter-pumped system displayed.

Configuration	**Maximum Output Power (W) (i)**	**Conversion Efficiency (%)**	**Full Power Amplifier Gain (dB)**	**Average Output Signal PER (dB)**
Co-Pump	222	86	17	17.5
Counter-Pump (ii)	220	85	16.5	16.5
Bi-Directional	230	88	17	16.3

(i) - Input Pump Power Maximum ~ 279W
(ii) - Following a 4% drop in output power during testing

Table 2 – Amplifier Performance Data for All Three Configurations

The signal source used for this study has a linewidth of ~ 0.8 nm. The output linewidth of the amplifiers for all configurations were also 0.8 nm. This linewidth is broader than what may be required for some combining techniques. Narrowing the input-signal linewidth can lead to the onset of non-linear effects within the amplifier fiber (SBS) and limit the output power performance (in this case below 200 W). The next phase of this study will investigate the amplifier performance with a narrower input-signal linewidth, as well as methods of improving the performance of the amplifier under such conditions.

SUMMARY

A monolithic, PM, high-power fiber amplifier has been demonstrated. Output powers of 220W or greater have been generated using three different amplifier designs, each capable of > 85% conversion efficiency, 16-17 dB gain and ~ 40 dB signal to noise ratio. The measured PER of 16-17 dB is respectable for a device such as this where a number of the components are only recently available. The PM-TFB combiner used in this investigation showed excellent performance overall; a very low signal insertion loss, a favorable pump insertion-loss change with increasing powers (coupling efficiency of 90% with 305 W input), low-operation temperature with 305W input (with water cooling) and good PER even when exposed to high pump powers. The only concern about the PM-TFB is its reliability in the counter-pump configuration, where it is exposed to both high pump and signal power simultaneously. The amplifier results presented here, however, do show that the technology to enable all-fiber high-power devices continues to evolve and future for these devices can be viewed with justified optimism.

ACKNOWLEDGMENTS

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