

Current Developments in High Power, Monolithic, Polarization Maintaining Fiber Amplifiers for Coherent Beam Combining Applications

D.P. Machewirth, Q. Wang, B. Samson, K. Tankala, M. O'Connor and M. Alam

*Nufern
7 Airport Park Road
East Granby CT 06026 USA
Ph: +1 860 408 5000, Fax: +1 860 408 5080
dmachewirth@nufern.com*

Abstract

Monolithic, all-fiber PM optical amplifiers have been investigated regarding components performance, amplifier design and narrow line-width amplification. PM-based components performed very well, the pump/signal combiner in particular handling > 300W pump power and still maintaining the PER of the input signal. A co-pumped amplifier configuration was chosen based on reliability and potential SBS mitigation (i.e. fiber length after the active fiber output). This system based on PLMA-YDF – 25/400 fiber appeared to give the best output power (155W-177W, depending on the length of passive delivery fiber), PER (~ 17 dB) and excellent beam quality ($M^2 = 1.1$). Altering the fiber temperature and length were necessary to provide the best results.

Introduction

Monolithic, polarization-maintaining (PM) optical-fiber amplifiers represent a promising technology as building blocks for power scaling to 100 kW levels. Advantages such as excellent beam quality, linearly-polarized output and narrow-linewidth amplification capability make them particularly attractive for combining techniques being investigated to reach such high power levels.

Output power from these amplifiers is largely dependent on three key technologies (a) the fiber design of the Polarization-maintaining Large Mode Area (PLMA) fibers utilized in these systems, (b) PM components made from these fibers and (c) pump diode sources. While LMA fibers, in general, have provided impressive output power numbers over the years¹⁻³, PM fiber-based amplifier components have only recently been manufactured. The PLMA fiber technology itself has progressed to the point where these types of components have become a reality. PM-components include Multimode Pump/Signal combiners (MPSCs) and Mode Field Adapters (MFAs). The former is a very important component in the amplifier architecture as it combines high-power pump light (generally at 976 nm or 915 nm wavelength) with the input signal and maintains the input polarization extinction ratio (PER) of the input signal. The improvement in all three aforementioned technologies are essential for engineering a monolithic PM amplifier system capable of high output powers.

This paper summarizes work performed at Nufern towards the development of all-fiber high power PM-amplifiers capable of single-frequency amplification (2-10 kHz). Investigations into amplifier design included different fiber designs as well as the application of external heating to the active fiber for improving amplification performance.

Results

Initial measurements were made to investigate the performance of both the components and amplifier (in co-pumped, counter-pumped and bi-directionally pumped configurations) using a 5W PM 1070 nm laser source (IPG Photonics) as the input signal. This source, being wider in line width (~ 0.8 nm), was chosen so that there would be no stimulated Brillouin scattering (SBS) limitations in output power and the amplifier configurations could be tested to their full extent. Other components used for the testing were: pump diodes capable of 50W output @ 976 nm (using 200/220 micron delivery fiber having a 0.22 core NA), a high-power polarization sensitive fiber-pigtailed optical isolator (Optics For Research), a PM-tap coupler (SIFAM Fiber Optics), a PM-MFA (ITF Optical Technologies), a PM-Tapered Fiber Bundle (TFB) pump/signal combiner (ITF Optical Technologies), a PLMA-YDF-20/400 active fiber with the core doped with Ytterbium (Yb^{3+}) for 1064 nm amplification, and a PLMA-GDF-20/400 passive fiber at the output. The co-pumped amplifier can be seen schematically in Figure 1. The passive and active fibers were both PM double clad fibers having 20 micron 0.06 NA cores, 400 micron 0.46 NA claddings and were made at Nufem.

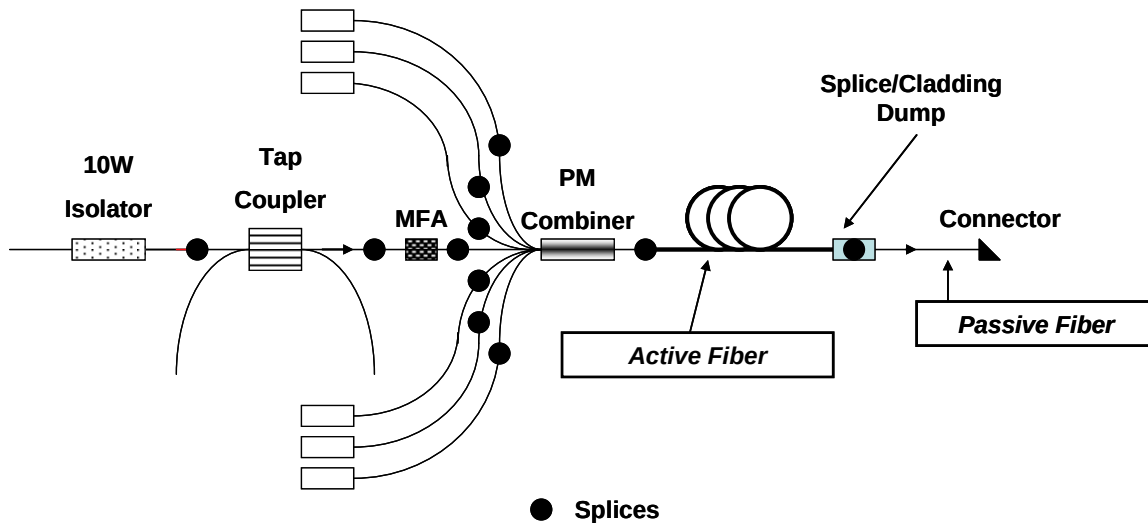


Figure 1 – Over 300W PM amplifier output power from a Bi-directionally pumped fiber amplifier

Although these initial tests have been described previously in more detail⁴, there were several observations. First, the high-power PM TFB combiners performed very well, handling $> 300\text{W}$ of pump power (from six 50W diodes). The PM-TFBs were water cooled. The pump insertion loss of the TFB was found to be power dependent, with the insertion loss actually decreasing with higher powers (from ~ 0.6 dB to ~ 0.4 dB). Although the exact mechanism is not fully understood, it is believed the combiner couples pump light more efficiently to the double clad output fiber with light propagating in a higher NA. Second, each amplifier configuration successfully generated $> 200\text{W}$ of amplified signal light at 1070 nm, reaching maximum powers of near 230W, and optical-to-optical slope efficiencies as high as 88% (the theoretical conversion efficiency for this pump/signal condition is $\sim 91\%$). Third, the measured PER for all configurations was a respectable 16 dB. Fourth, it was observed that the counter-pump amplifier design had a slight power decrease (within the first few minutes of operation) that was attributed to the PM-TFB. The output power and PER data measured for the highest output power test, for each amplifier configuration, are shown in Table 1.

From these observations, it was concluded that the co-pumped amplifier design would be best suited for testing using a narrow line-width source as (a) the PM-TFB would not be handling so much power (both 300W of pump light and $\sim 200\text{W}$ of signal light, worse case, for the counter-pump condition) and (b) the SBS threshold may be higher if the shortest length of fiber after the YDF could be used (given a

connectorized passive fiber was to be included in the design). It is noted, however, that the maximum amount of output power from these systems was achieved in the bi-directional pump scheme, where one can couple more than 6 pump diodes (8 diode pumps were used for this study) and > 300 W signal power was achieved (Figure 2). This indicates the PLMA fibers, both YDF and passive, are well capable of handling both the large amounts of pump power and/or the efficient generation of high signal powers required for these amplifiers.

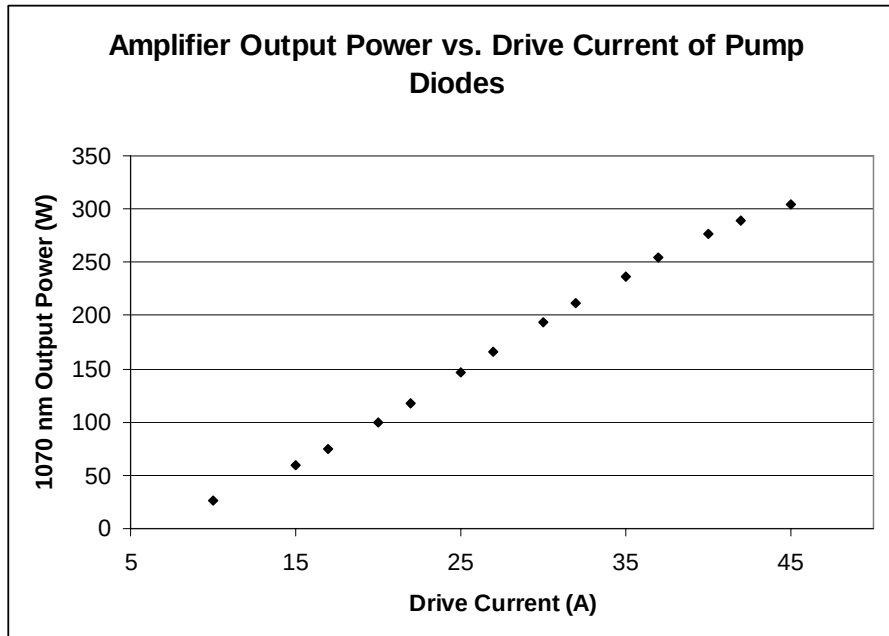
Table 1 – Summary of measured PM amplifier data using several amplifier architectures

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

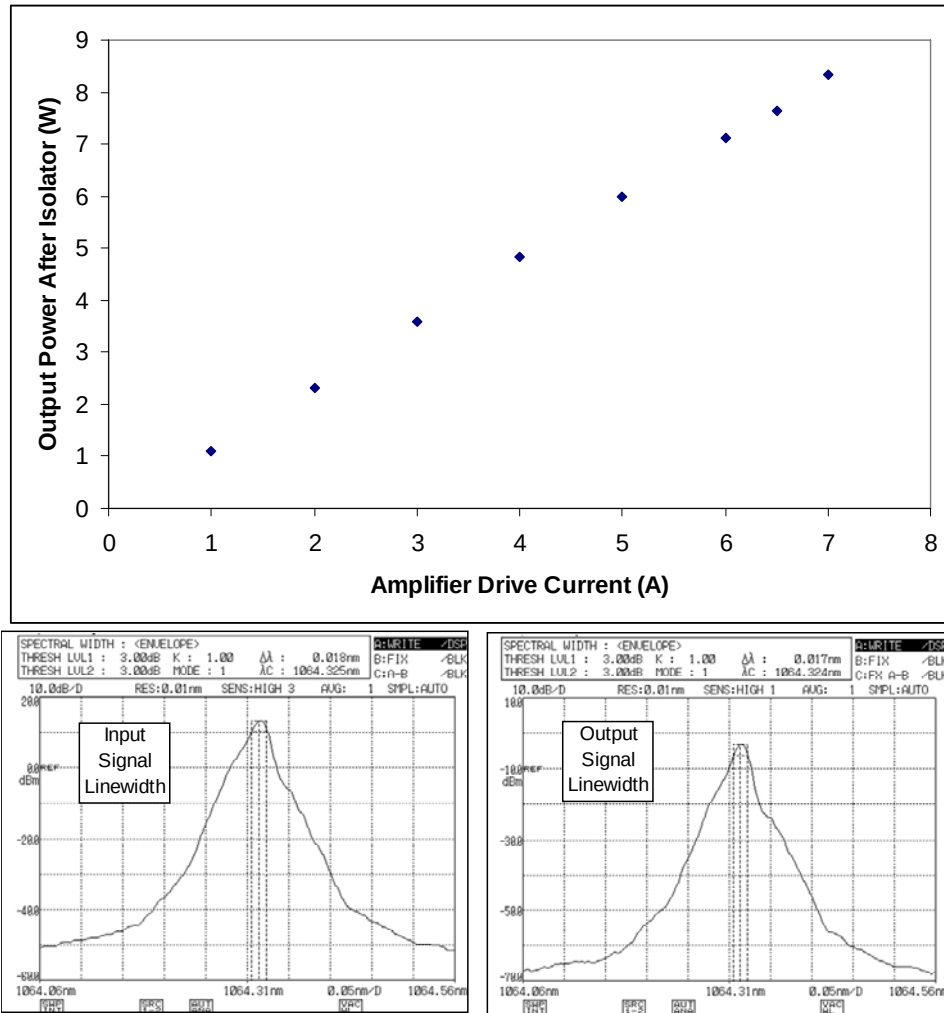
(ii) - Following a 4% drop in output power during testing

Figure 2 – Over 300W PM amplifier output power from a Bi-directionally pumped fiber amplifier



The co-pumped amplifier configuration using the PM-20/400 fiber was then subjected to a series of measurements using a narrow line-width (~ 5 kHz, NP Photonics) 1064 nm input signal. This signal only had an output power of 50 mW; therefore it had to be amplified with a 10W narrow line-width amplifier, manufactured by Nufern (PER > 20 dB), bringing the input signal to sufficient levels for high power amplification. Figure 3 shows the output of the amplifier and the high power 10W isolator (insertion loss of isolator ~ 1.5 dB), as well as the measured line-width of the input and output signal via an optical spectrum analyzer (OSA). Although the OSA resolution is nowhere near what is required to see kHz – low MHz line-widths, the measurements show the resolution-limited line-width (0.017 nm) after amplification exhibits no gross broadening of the input signal.

Figure 3 – Output Power From 10W Single-Frequency Amplifier (post-isolator) and line-width measurements of input and output signal

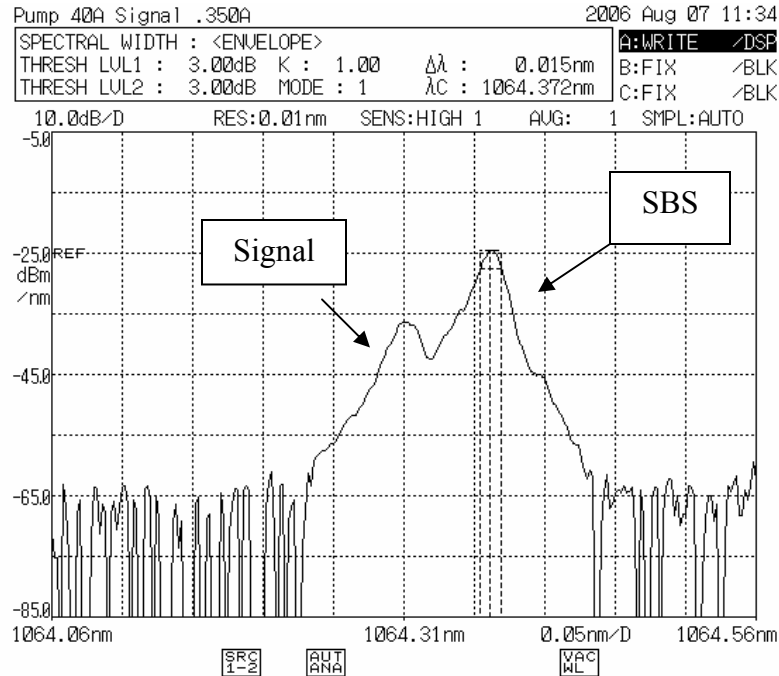


The 20/400 active fiber for 200W amplifier was ~ 9.5 meters, with the majority of fiber being held in a cooling coil to both cool the YDF as well as the splice between the YDF and the PM-TFB. The coil diameter was appropriately chosen to obtain single mode behavior⁵, where the M^2 of the output beam was on the order of 1.1 or less. There was 1 meter of passive delivery fiber, PLMA-GDF-20/400, on the output of the amplifier. A 2x2 optical tap, located between the isolator and the MFA, was used to monitor the input signal power (front tap leg) as well as any backwards-traveling power generated by SBS (back tap leg).

Under this configuration, using the amplified narrow line-width input signal, the maximum amplified output power was ~ 30W before an increasingly large back-scattered signal was observed from the backward leg of the optical tap. Using an OSA to measure the signal from this tap leg confirmed the signal to have the signature of SBS, as seen in Figure 4. To improve on this result, other tests were performed utilizing (a) shorter fiber lengths, and (b) external temperature adjustment of the fiber. The former is quite well known for reducing SBS, but does have a negative effect on overall efficiency as the fiber absorbs less pump-light. The latter method has theoretically been described⁶, where temperature changes along the fiber length cause an increase in SBS onset threshold. This temperature change can be done by heating or cooling, as long as there is some significant delta along the total fiber length. Based on this line of thinking, it is quite clear that the initial measurement yielding 30W amplification was in the least desirable

configuration, temperature-wise, as the majority of fiber was uniformly cooled over just about the entire length.

Figure 4 – SBS signal detection during amplification test using PM 20/400 fiber



Several measurements were performed, using different heating configurations and different fiber lengths. For all tests, some active fiber still remained on the cooling coil (which was still deemed necessary based on the amount of pump being used and to keep beam quality), but the fiber outside the cooling coil could either be left in air, or heated in certain sections. Depending on the condition, the output power from the amplifier varied between 40W and ~100W (the latter power without any passive fiber on the YDF output and having a section of the ~6m of YDF length heated). The maximum heating temperature used was 80 C. Use of higher temperatures would give even better results but this temperature limit was chosen to ensure longevity of the fiber and would likely be the limit in a practical system. Although the amplifier architecture was less than ideal, these tests did show that optimized heating of the fiber, along with length tailoring, could substantially improve the narrow line-width amplified signal output power.

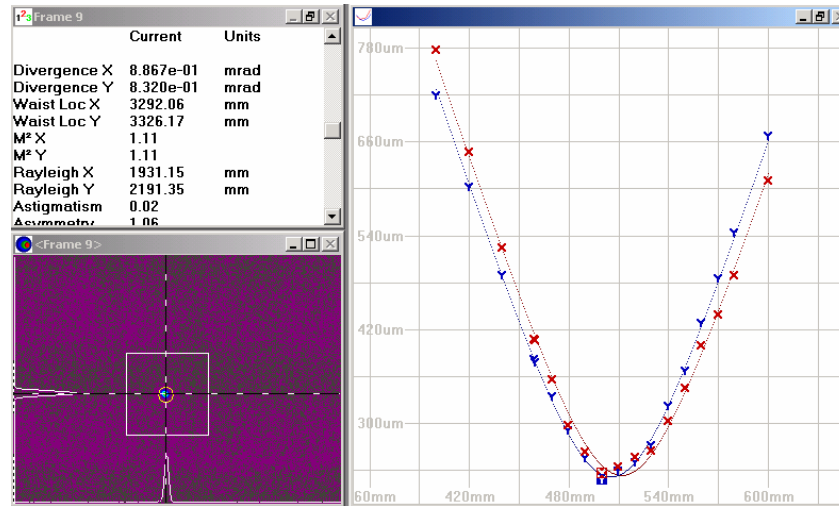
To improve the SBS performance, the PLMA-20/400 active and passive fibers were removed and replaced with similar Nufern PLMA-25/400 fibers (PLMA-YDF-25/400, PLMA-GDF-25/400). The differences between the fiber types were the core size and the cladding absorption at 976 nm (for the YDF), which helped reduce the length of the PLMA-YDF-25/400 to 6.5 meters. The choice of a 25 micron core was made to not only help reduce SBS but also to have a high probability of achieving diffraction limited beam quality ($M^2 \sim 1.1$). There was ~1m of passive PM 25/400 fiber for the initial measurements.

Initial testing of the fiber with the aforementioned broadband 5W PM laser at 1070 nm produced excellent results. Over 200W output power was achieved with ~17 dB PER and a beam quality of $M^2 \sim 1.1$ (Figure 5). It is noted that, for the configuration pertaining to these measurements, only the active fiber and output passive fiber was changed from the amplifier layout seen in Figure 1 (PLMA-25/400 replacing PLMA-20/400). The PM-TFB still had a PLMA-GDF-20/400 double clad fiber on the output.

Experiments were then repeated for the PLMA-25/400 based amplifier system using the narrow line-width amplified signal source. For reference, with all the active fiber coiled in the cooling coil, the amplifier output power was increased to 60W, versus ~30W with the PLMA-20/400 fiber. This difference is larger than one would expect from a core size change alone (assuming a change similar to the core area ratio) and

could possibly be due to the comparably shorter fiber length. When heating of the fiber and length adjustments were made, the largest output power (no GDF) was $\sim 177\text{W}$. The PLMA-YDF-25/400 length was ~ 5 meters. It is once again noted that the temperature of the heated fiber section was $\sim 80^\circ\text{C}$. The output power of the amplifier with the PLMA-GDF-25/400 fiber varied between 155W and 177W , depending on the GDF fiber length. These high output power levels show that an all-fiber amplifier can be engineered to amplify narrow line-width input signals to high powers and still maintain near diffraction limited beam quality and good PER.

Figure 5 – Beam Quality at $> 200\text{ W}$ output for the PM 25/400 fiber amplifier system



As a result of this work, a prototype high-power PM fiber amplifier is being designed that will incorporate a specially designed fiber heater. The heater will enable the user to obtain higher amplifier output powers as the input signal line-width becomes sufficiently narrow that SBS becomes an issue. Future potential improvements could include work in fiber design (potentially larger core sizes and 976 nm cladding absorptions, beam quality would need investigation) and pump diode brightness ($> 50\text{W}$ into 200/220 micron, 0.22 NA fiber).

Summary

Work has been performed for an all-fiber, monolithic, high power PM amplifier. The PM-based components recently developed appear to perform quite well, but still need some investigation when high pump and signal power are simultaneously propagated through them. The amplifiers themselves were capable of $> 85\%$ optical-to-optical efficiency and are approaching the theoretical efficiency maxima. SBS measurements confirmed the original belief that the PLMA-25/400 fiber system would perform better than that using 20/400 but that heating either fiber in certain configurations greatly improved SBS performance. The amplifier design is currently being engineered for building multiple units that would be used for coherent combining experiments.

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