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Jay W. Dawson
Eric C. Honea
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High brightness spectral beam combining to 8.2 kW

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Abstract: We report on the spectral beam combining of four narrow-linewidth fiber amplifier chains running at different wavelengths. The main amplifier stage consists of a large mode area photonic crystal fiber delivering more than 2 kW of optical power. The four output beams are geometrically (incoherent) combined using a polarization-independent dielectric reflective diffraction grating to an output power of 8.2 kW preserving the beam quality of the individual fiber amplifiers.

OCIS codes: (140.0140) Lasers and laser optics; (140.3510) Lasers and laser optics: Lasers, fiber

1. Introduction

Yb-doped fiber lasers at 1 μm wavelength have been established as a reliable power-scalable laser architecture in the past years. The power limit is usually set by damage, thermal issues or nonlinear optical effects. The generation of output powers above such limits of a single fiber is considered in current research activities. Coherent and incoherent combining schemes for multiple beams were demonstrated. A promising concept is the incoherent spectral beam combining (SBC) relaxing the requirements for phase control of the individual beams. Using volume Bragg gratings, 770 W have been obtained already with the drawback of being influenced by thermal drifts at high power levels [1, 2]. Output powers up to 2 kW based on fiber amplifiers and a polarization independent dielectric grating have been reported by our group most recently.

In this contribution we report on further power scaling by spectral beam combining. The four individual amplifiers have been scaled up to a power of >2 kW. With a combining efficiency of 99 % we obtained a power of ~ 8.2 kW. The main amplifier fibers support only a few modes resulting in a good beam quality and the beam combination setup preserves this beam quality.

2. Experimental

The experimental architecture is similar to the one published previously [3] and is shown in Fig. 1. The individual amplifiers are seeded by a fiber coupled wavelength tunable external cavity single-frequency diode laser (ECDL) delivering 20 mW. The emission wavelength are tuned to 1040 nm, 1048 nm, 1056 nm and 1064 nm, thus a separation of 8 nm. To enhance the SBS threshold a linewidth control is applied, which employs a modulation of the ECDL's driver current with a noise generator resulting in an increased seed-signal bandwidth of ~ 90 pm. The seed signal is amplified in the first amplification stage to a power of ~ 500 mW. This signal is launched into the second pre-amplifier stage using a 1.6 m long, polarization-maintaining photonic crystal fiber having a 40 μm signal core and a 200 μm pump core. An output power of ~ 20 W in a linearly polarized and diffraction-limited beam is obtained. The preamplifiers are protected against back reflections from the main amplification stage by optical isolators.

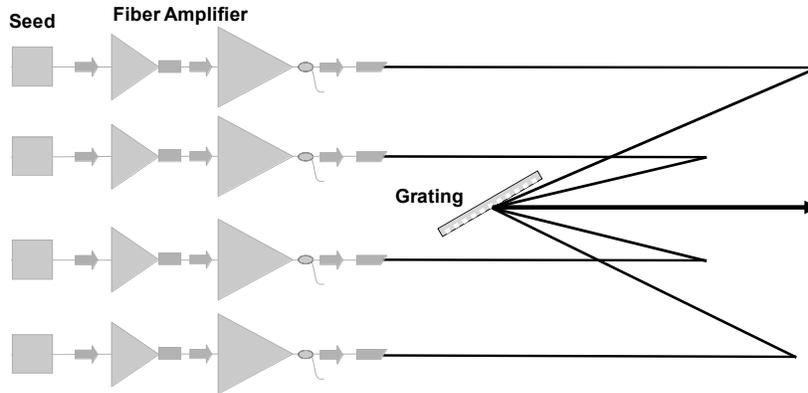


Figure 1: Schematic experimental setup for the spectral beam combining.

The main amplifier-stage consists of a ~ 12 m long ytterbium-doped photonic crystal fiber prepared for high power operation [4]. The active core of the fiber has a measured mode field diameter for the fundamental mode of ~ 33 μm . The pump core is defined by an air-cladding region and has a diameter of 500 μm and a numerical aperture of 0.55. The stage is pumped at 976 nm through one fiber facet in a counter propagating configuration by a fiber coupled diode laser. The grating, which is used as combining element, is a highly efficient reflective diffraction grating (binary grating, 960 lines/mm), optimized for both TE- and TM-polarization, hence, for non-polarized light. Thus, no polarization control of the main amplifier is required.

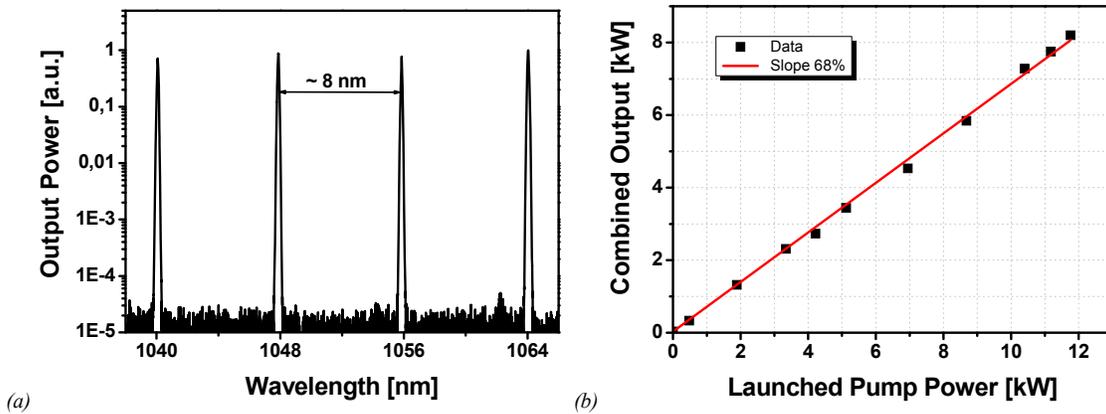


Figure 2(a): Combined spectrum, (b) Output characteristic after the grating.

Each amplifier is able to generate an output power of ~ 2.1 kW limited by the available pump power. However, the beam quality is decreased with increasing power due to spatial hole burning that enables the onset of higher order modes. The beam quality stays close to diffraction-limited of $M^2 < 1.5$ up to a power of 500 W but decreased to $M^2 \sim 4$ at 2 kW. The four beams have been geometrically overlapped in near and far field. The combined beams spectrum is shown in Fig. 2(a). The output characteristic after the combination is shown in Fig. 2(b). The combining efficiency is $\sim 99\%$ measured by the power in the 0th diffraction order. Thus, a combined output power of 8.2 kW could be obtained. The measured beam quality at 7.2 kW was $M^2_x = 4.3$ and $M^2_y = 4.2$.

3. Summary and conclusion

We demonstrated the spectral beam combination of four narrow-linewidth photonic crystal fiber amplifiers. Each individual beam has a spectral width of ~ 90 pm at an output power of ~ 2.1 kW and a beam quality of $M^2 \sim 4$. The polarization independent grating allowed an efficiency of 99%. The combined beam has an average power of 8.2 kW (pump power limited) with a good beam quality. Investigations on further power scaling by adding additional

channels are under progress. Diffraction limited beam quality will be preserved by advanced fiber designs enforcing single mode operation even at higher output power.

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A 967 W Single Mode All-Fiber PM Yb PCF Fiber Amplifier

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ABSTRACT

We report on the development and performance of a monolithic, all-fiber, polarization maintaining (PM), Yb-doped photonic crystal fiber (PCF) type fiber amplifier. The key components of the amplifier are a novel multi fiber-coupled laser diode stack and a monolithic 6+1x1 fiber pump/signal multiplexer. The precisely aligned 2-D laser diode emitter array found in laser diode stacks is utilized by way of a simple in-line imaging process with no mirror reflections to process a 2-D array of 450 elements into 3 400/440 μ m 0.22NA pump delivery fibers. The amplifier in this work utilizes two laser diode stacks, one at 915 nm and the other at 976 nm for six total delivery fibers, three per stack, with an aggregate available pump power of 1.65 kW. The fiber combiner is an etched air taper design that transforms low numerical aperture (NA), large diameter pump radiation into a high NA, small diameter format for pump injection into an air-clad large mode area PCF, while maintaining a constant core size through the taper for efficient signal coupling and throughput. The fiber combiner has 6 400/440/0.22 core/clad/NA pump delivery fibers and a 20/440 PM step-index signal delivery fiber on the input side and a 40/500 PM Yb doped PCF on the output side. The etched air taper transforms the six 400/440 μ m 0.22 NA pump fibers to the 500 μ m 0.55 NA core of the PCF fiber with a measured pump combining efficiency of 92% with zero brightness drop. The combiner also operates as a stepwise mode converter via a 30 μ m intermediate core region in the combiner between the 20 μ m core of the input fiber and the 40 μ m fiber core of the PCF with a measured signal efficiency of 90% while maintaining polarization with a measured PER of 20 dB. A seed laser was formed using one of the 915 nm pump legs to end pump a PLMA 20/400 Yb-doped fiber laser which provided 80W of seed power at 1085nm. This seed signal was then fed through the fiber pump/signal combiner with the remaining 5 pump legs into the large Yb-doped PCF fiber. In this configuration a total power of 967 W was observed with a slope efficiency of over 75%. We report the signal coupling efficiency and power handling capability as well.

Keywords: Fiber Amplifier, Power Amplifier, Laser Diode Stack, Fiber Combiners, Photonic Crystal Fiber

1. INTRODUCTION

All-fiber high power fiber amplifiers are a critical component for defense and industrial applications because they provide rugged and reliable operation of a compact and relatively low cost coherent light source that can be combined as part of a distributed amplifier array or deployed in the gain section of an industrial fiber laser. Such power amplifiers are highly sought after because they offer the prospect of high levels of pump power integration in large mode area (LMA) PCF fibers, and add significantly to the ruggedness and reliability of the device by eliminating the losses and alignment problems inherent in free-space fiber amplifier architectures. A significant engineering challenge for such power amplifiers lies in the development of key pump and combiner components for monolithic integration. Current kW class fiber lasers achieving single mode outputs have been created by using LMA type fibers with multi-element laser diode pumps that are combined to provide pump powers of approximately 1 kW [1]. For powers above 1 kW, large free space coupled stacks have been successfully employed to end pump LMA step-index and PCF type fibers [2-3]. For multi-kW single mode fiber amplifiers, a LMA PCF has many advantages with the ability to fabricate a very low numerical aperture (NA) core and a large high NA pump cladding.

Steady progress in high power all-fiber amplifiers has been stymied somewhat due to the high cost and complexity of the pump lasers. These pumps whether created through the alignment and focusing of combined independent single elements, 1-D laser diode bars or 2-D laser diode stacks suffer from a high number of very intricately aligned optical micro elements at 0.1 μ m level alignment tolerances. To address this issue, we have developed a multi-fiber coupled laser diode stack which parallel processes over 450 individual laser diode emitting elements into three 400/440 μ m fibers.

Fused fiber combiners have been a critical component in current all-fiber lasers and amplifiers because of their

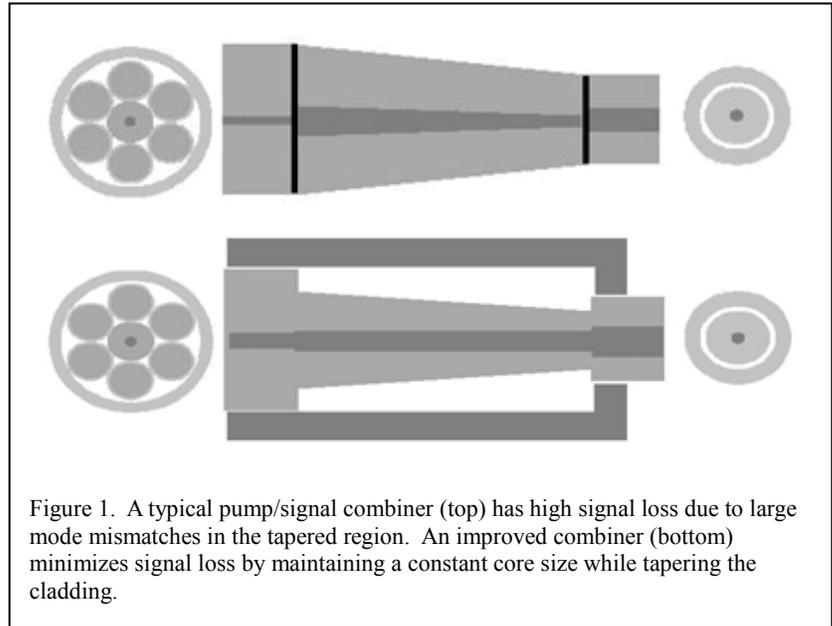
ability to efficiently combine both pump and signal light into active double clad fibers. Current fiber combiners [4-8] have coupling efficiencies of >95% for the pump and >85% for the signal. Although the performance of these combiners is very respectable, there are limitations that prevent this type of coupler from being used effectively in very high power (multi-kW) LMA PCF amplifiers and lasers. Foremost, in a typical combiner, a bundle containing a signal fiber surrounded by pump fibers is heated and stretched down to a waist that matches the diameter and NA of the active double clad fiber as shown in Fig. 1. Because the signal fiber is tapered down along with the pump fibers, the resulting small core diameter of the signal fiber can have a significant mismatch to the core of a LMA double clad fiber. The large mismatch of mode field diameters leads to unacceptably high loss especially for LMA PCFs.

Creating all-fiber PCF amplifiers has proven to be difficult, especially designs that can utilize large diameter pump fibers (400 μm or greater) that can be bundled into 6+1x1 configurations for very high power operation. To address this challenge, we have developed an all-fiber 6+1x1 pump/signal combiner for a LMA PCF that combines the output of six 400/440 μm , 0.22 NA pump fibers and a 25/440 μm PM signal fiber into a taper that preserves the diameter of the core while the multimode pump light is coupled into an active fiber with smaller diameter and high NA. With this improved design, it is possible to reduce signal losses to <0.5 dB, while maintaining 92% pump throughput.

In this paper, we will detail the construction and performance multi-fiber coupled diode laser stacks and the 6+1x1 pump/signal combiner and demonstrate the use of these components in the operation of an all-fiber, PM, single mode Yb PCF power to achieve an output power of 967 W in quasi-CW operation.

2. MULTI-FIBER COUPLED PUMPS

Efficient pump integration is perhaps the most critical task in creating compact and efficient all fiber multi kW amplifiers. The essential element is to create a pump integration system where high brightness fiber coupling is accomplished via combining a large number of individual emitters in as parallel a process as possible. The unique spatial emission properties of high power broad area laser diodes allow for the creation of Symmetric Brightness Units (SBU's) where a number of emitters are aligned in the direction of their near diffraction-limited fast axis emission planes, such that the combined brightness matches the slow axis brightness of a single or multiple emitters. Our approach takes advantage of the alignment precision inherent in a 2-D array of broad area emitters found in a laser diode stack. By creating the simplifying approach to subdivide the 2-D array into 3 SBU's for efficient fiber coupling, the number of required optical components is greatly reduced as is the optical loss of the system. For the amplifier, 2 multi-fiber coupled stacks were created, one operating at 915 nm and the other at 976 nm. These multi fiber pumps along with their aggregate fiber coupled power output are shown in figure 2.



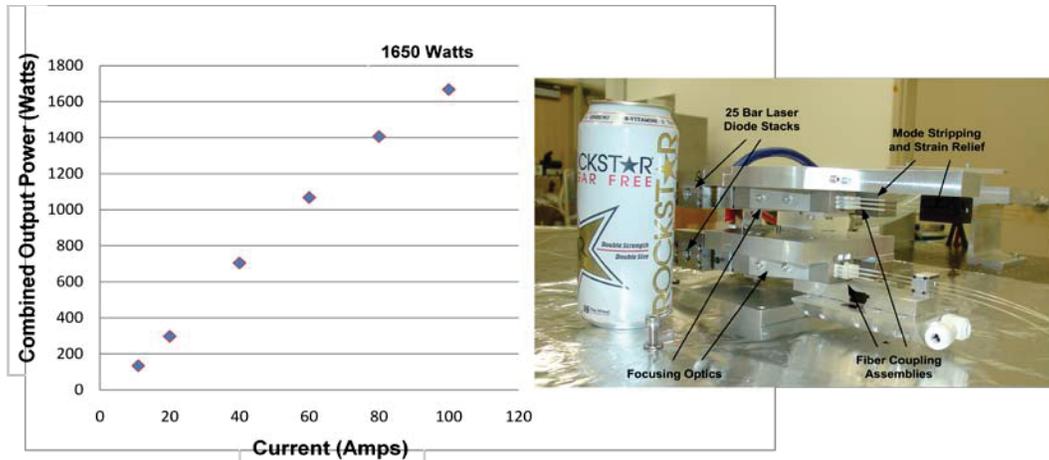


Figure 2. Photograph of two 25-bar fiber coupled stacks with a graph showing a total coupled power of 1650 Watts

From the photograph in Fig. 2, the very compact nature of this technical approach is evident. Continued development is underway to improve fiber coupling efficiency and power handling capability. It is envisioned that through this approach a compact, lightweight, and low cost pump integration source of over 4kW in aggregate power will be possible.

3. 6x1+1 ETCHED AIR TAPER FIBER COMBINER

Much of the work completed in developing these devices have been described elsewhere [9]. A summary of the process steps involved in creating these combiners is shown in Figure 3.

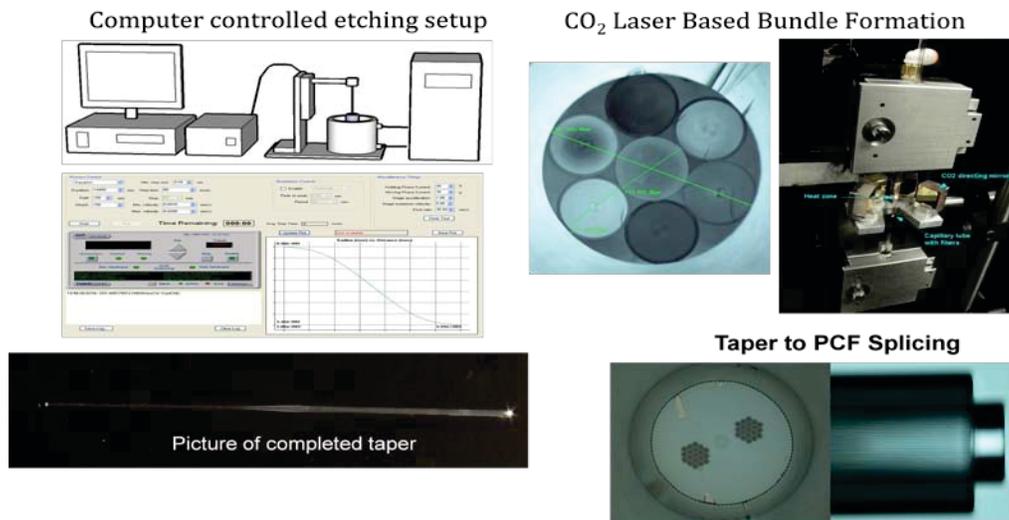


Figure 3. Processes for Creating an Etched Air Taper Combiner. CO₂ based laser bundle formation (upper right). Computer controlled etching process (upper left) Taper to PCF splicing (lower right)

To create an etched air taper combiner, a 6+1x1 bundle is created with the pumps and the signal fiber in the center by collapsing a glass capillary around the bundle such that there is no deformation to the pump or signal fibers. At the time this process was created, there were no commercially available fiber processing units to process bundles close to two mm in diameter. To overcome this, a bundling station was created using a CO₂ laser to provide the proper uniform heating for optimum bundle collapse. Next a uniform adiabatic taper is created by immersing a glass rod (with core) into an etchant solution and then using a computer driven process to remove the rod from the etchant solution. Finally the three components of the assembly are spliced together to create the bundle. For the amplifier pump combiner, 6 400/440 μm 0.22NA pump fibers were bundled with a 20/440 μm PM signal fiber. An etched air taper region was created from a

1.2mm outer diameter/30 μm core pulled fiber rod. The bundle/taper spliced assembly was then spliced to the 40/500 μm PM Yb-doped PCF gain fiber. The PCF was air-clad with a 0.55 NA for the inner pump cladding. Pump transfer efficiency was measured to be 92% with no brightness drop while the signal transfer efficiency was measured to be over 90%. A single plane of polarization from input signal to gain fiber was maintained throughout the device. We measured a PER of 20dB through the combiner.

A key to high power operation of the combiners is the packaging. Even with losses on the order of 5%, 2kW operation requires in excess of 100W to be effectively dissipated from a very small physical space. For these combiners, a special high power dissipation package was designed and developed. A sample device was power tested in the laboratory of Prof. A Galvanaskas at the University of Michigan. The results of this testing is shown in Fig. 4. With 1.5 kW of launched pump power, we measured nearly 1400 W of combined pump power out of the combiner for a transmission efficiency of 92%. During the entire testing cycle, a thermal camera was used to observe the fiber combiner under high power operation. The air taper, taper to PCF splice and strain relief are clearly shown in Fig. 4. Since this device is being operated at zero brightness drop, the largest point of loss in the combiner is at the taper to PCF splice (about 5% to 6%). At this loss point, the PCF fiber is etched to create a scattering/mode stripping point to remove the non-coupled light. While the vast majority of this light is directed out of the fiber at this point, a small amount of the residual light is guided and captured at the strain relief point. At the strain relief point, the highest temperatures in the combiner were observed, approximately 104°C for 1.5 kW of input power. This temperature is well below the 260°C temperature limit of the high temperature silicone used to secure the fiber. Considering how well this combiner performed at the 1.5kW level, we estimate that the combiner in its current level of development is capable of 2kW pump combining.

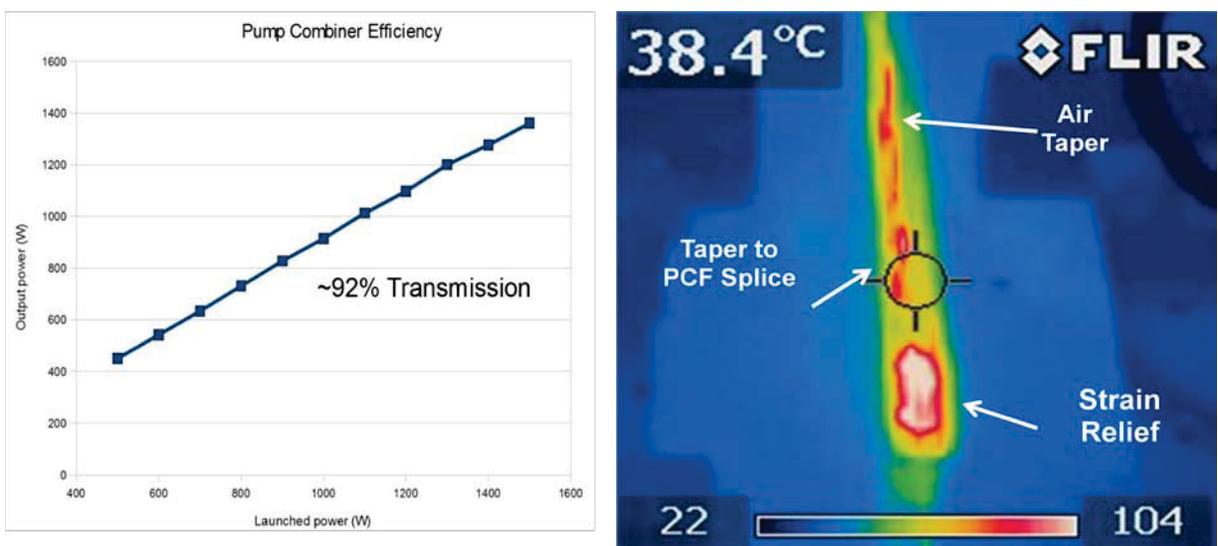


Figure 4. (Left) Power testing of the etched air taper combiner demonstrating 92% pump combined efficiency with an input power of 1.5 kW. (Right) A thermal camera image of the combiner under high power operation.

4. POWER AMPLIFIER CONSTRUCTION AND OPERATION

Due to the difficulty in obtaining 100 W fiber laser seed sources and in order to completely characterize the fiber amplifier, our own CW seed source was fabricated by taking one of the 200 W pump legs from the 915 nm fiber coupled stack and end pumping a 20 m length of 20/400 μm Yb-doped LMA fiber with a HR FBG on the input side and an 8% FBG output coupler. The seed source was first fabricated and characterized. Approximately 75 W of output power at 1085nm was achieved and available to use as a seed to the power amplifier stage. This seed source was then fed through the signal port of the combiner. The remaining 2 ports of the 915nm source and the 3 ports of the 976nm pump were spliced to 5 of the 6 ports on the combiner. The combined pump and signal was then spliced to the 40/500 μm PM Yb PCF fiber. At the output of the fiber amplifier, a power meter was placed a distance from the fiber with an aperture to

separate the signal from the unabsorbed pump. The schematic of this amplifier is shown in figure 5.

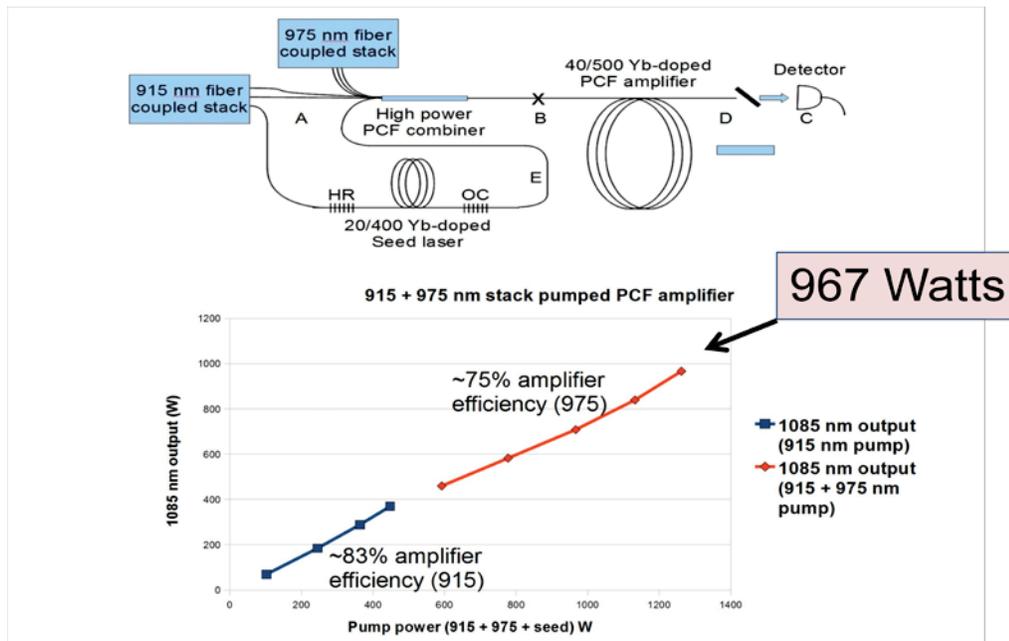


Figure 5. Schematic of the 976 W fiber MOPA showing the configuration of the multi-fiber coupled stacks and 6+1x1 pump-signal multiplexer.

Also shown in Fig. 5 is the input vs. output power graph for the fiber amplifier. In order to avoid fiber damaging self Q-switching, the 915 nm pump was turned on first, to initiate the seed laser and pump part of the power amplifier in a low gain configuration. With 915 nm pump turned on, an output of the power amplifier of 300 W was observed with an absorbed power slope efficiency of 83%. The addition of the 976 nm pump increased the power amplifier output to a maximum of 976 W with an absorbed power slope efficiency of approximately 75%. A visual inspection of the beam indicated that no other higher order modes were present.

Several improvements are envisioned for this amplifier. First, pumping with both sources at 976 nm would allow for a shorter fiber to be used and optimized for a common wavelength. Second improvements in fiber coupling efficiency for the pumps would allow for more pump power to be provided to the amplifier. Currently the seed source has the broad spectrum characteristic of fiber lasers. Utilizing narrow band seeds will require the use of more specialized PCF core designs than the one currently employed. Finally in the current set up none of the components are properly heat sunk so to avoid component overheating. As such, the system is run with a 10ms pump pulse at 10 Hz. Proper heat sinking will allow for true CW operation.

5. CONCLUSIONS

Successful operation of an all-fiber 967 W Yb-doped PM PCF fiber amplifier has been achieved through the development of 2 key amplifier components; namely, a multi-fiber coupled laser diode stack and a high power capable etched air taper 6+1x1 fiber pump/signal combiner. Not only have these two key components have they been successfully demonstrated and operated, the critical processes for assembling these components have been fully worked out allowing for the fabrication and production of multiple units. With continuing improvements, the goal of fielding near diffraction limited, highly linear power amplifiers operating near 3kW or higher in ultra compact, highly rugged and reliable enclosures will be realizable.

The development of the key amplifier components was funded under ARL contract W911NF-07-2-0063. Fabrication and demonstration of the power amplifier was funded under AFRL contract FA9451-10-M-0078. Adaptation of this technology for pulsed applications was funded under NASA contract NNX10CD89P.

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Modal content reconstruction of fibers for high-power applications

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New fiber designs have been increasing the performance of high-power fiber lasers. To lower the impact of nonlinearities, large-mode areas are required, which leads to fiber designs supporting a few modes. In order to ensure an excellent beam-quality from these sources, a high premium is put on modal discrimination. Thus, it is essential to develop experimental methods that reveal the modal content and modal weights. One of the promising new methods is spatially and spectrally resolved (S^2) imaging, as it does not make any assumption on the properties of the fiber to be tested [1, 2]. However, the technique makes it difficult to analyze fibers in which the modes exhibit small relative group delays (e.g., in the case of large mode area fibers). Particularly, the spectral interference fringe spacing becomes non-specific as group-velocity dispersion plays a dominant role for a broad spectrum, which is required to record the spectral interference.

In this contribution, we demonstrate, for the first time to the best of our knowledge, a method that enables modal reconstruction at small intermodal delays even for spectral bandwidths smaller than that needed for measuring a single fringe of an interference spectrum. The novel technique is based on optical low-coherence interferometry (OLCI). In contrast to previous work [3, 4], we also account for the influence of group-velocity dispersion (GVD) on the modal weights and determine the correct multi-path interference (MPI) values in a few-mode fiber. This requires no knowledge about the optical properties of the fiber to be characterized. For a spectral bandwidth as small as 4 nm, we measure intermodal delays as short as 2.8 ps at mode-extinction values up to 18 dB. These values are specific to the fiber under test, but our technique is capable of measuring intermodal delays as short as the ultimate physical limit in form of the coherence time. This makes it highly attractive for the characterization of the next generation of high-performance fiber laser.

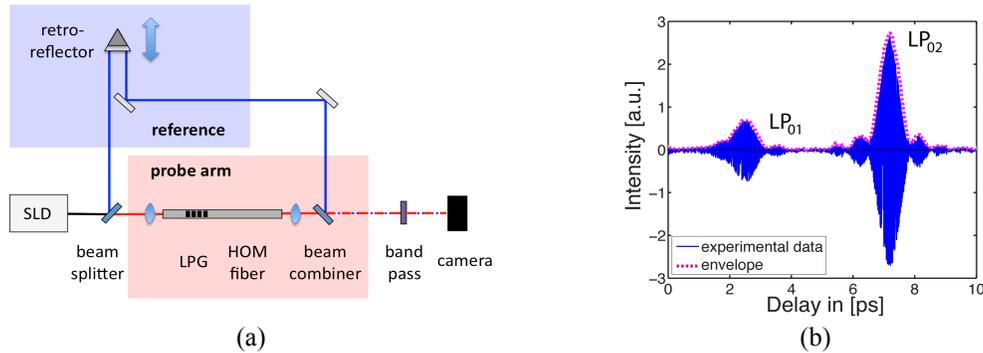


Fig. 1 (a) Schematic of the setup, which is based on a Mach-Zehnder interferometer (SLD: superluminescent diode, LPG: long period grating, HOM: high order mode) (b) Cross-correlation trace for the entire image (data is offset corrected) (bandpass filter is at $\lambda=780$ nm)

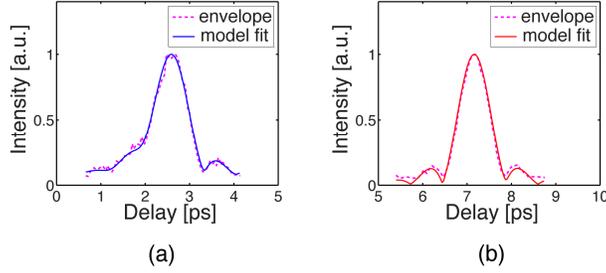


Fig. 2 (a) Fit of the model to the envelope of the experimental data, shown in Fig. 1 (b) for the first peak (corresponding to LP₀₁) and (b) for the second peak (LP₀₂)

A typical schematic of the experimental setup for OLCI measurements is shown in Fig. 1(a). The near-field at the output of the fiber is imaged onto a camera, and interfered with the collimated, expanded beam of the reference arm. The few-mode fiber under test is the final element of a module ($L=0.6$ m) consisting of a single-mode fiber, a turn around point long-period grating (TAP LPG), and the higher-order mode (HOM) fiber ($L=0.4$ m) [5]. The LPG yields a well-defined mode conversion efficiency from LP₀₁ core-mode to LP₀₂ core-mode. To detect the cross-correlation signal between the reference and the different modes, a computer-controlled translation stage has been built in the reference arm in order to scan across the modal delays for each individual mode in the signal arm. Figure 1(b) shows an example of the coherence trace (integrated over all pixels of the camera). The peaks in the trace correspond to the two different modes that have been excited in the HOM fiber. In general, the recorded signal contains a high-frequency contribution, as shown in Fig 1(b), the envelope of which contains all the information of interest.

We have developed an analytical model that accounts for the influence of dispersion on the cross-correlation data. Specifically, dispersion decreases the amplitude of the peaks in the cross-correlation signal. Fig 2 (a) and (b) show the result of the fitting of the model for the two peaks seen in Fig. 1(b). Since this fitting is based on the same spectrum, the difference in shape is solely due to the impact of dispersion. In this way, the group-delay dispersion values are found for every mode. By tilting the 4-nm bandpass filter, these parameters can be retrieved as a function of wavelength. Fig. 3(a) and (b) shows the dispersion and relative group-delay vs. wavelength, respectively. Using these parameters, the mode profiles are determined by fitting the analytical model at every pixel. In this way, the LP₀₁ and LP₀₂ mode have been retrieved, as shown in Fig. 4(a) and (b), respectively. Moreover, the relative (dispersion-corrected) weights of the modes can be obtained. To demonstrate the accuracy of the method, in Fig. 4(c), we show the MPI as a function of wavelength. These values match well with the mode conversion efficiencies independently measured by recording the LPG loss spectrum (the MPI is defined as $10 \log_{10}(\iint I_{LP01}(x,y) dx dy / \iint I_{LP02}(x,y) dx dy)$).

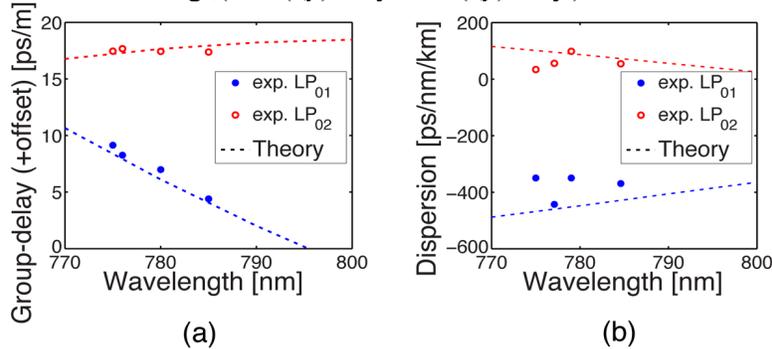


Fig. 3 (a) Group-delays of the two modes, and (b) Dispersion as a function of wavelength position of the bandpass

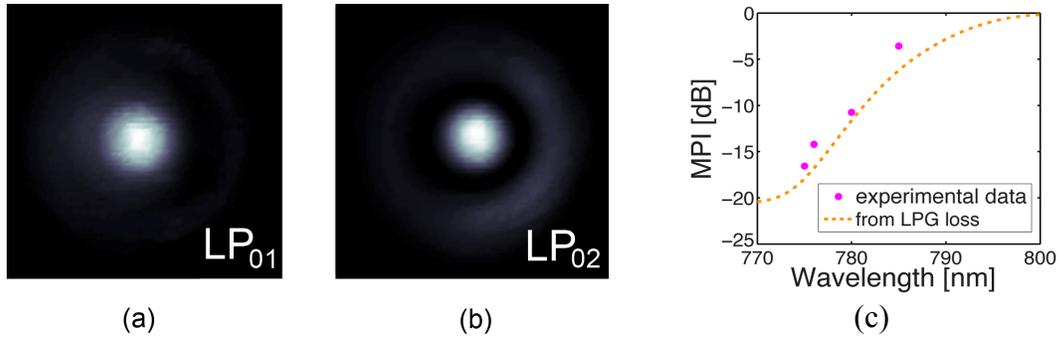


Fig. 4 (a) and (b) Retrieved modes at a wavelength of 780 nm; (c) Multi-path interference as a function of the spectral position of the tunable bandpass filter.

In conclusion, for the first time, to the best of our knowledge, the impact of dispersion on the modal weights of a few-mode fiber has been demonstrated. This has allowed us to accurately determine modal weights even in fibers whose modes have small relative group delays but distinct dispersive behavior. This makes it highly attractive for the characterization of fibers that are being developed for next-generation high-power fiber lasers.

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Power-scalable internal frequency doubling scheme for continuous-wave fiber lasers

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ABSTRACT

We describe a simple power-scalable concept for efficient second harmonic generation in a cladding-pumped continuous-wave fiber laser. Our approach makes use of an internal resonant enhancement cavity to increase the intracavity power and second harmonic conversion efficiency without the need for active cavity length control and stabilization. This technique has been applied to a cladding-pumped Yb-doped fiber laser yielding 15 W of linearly-polarized continuous-wave green output (at 540 nm) for 90 W of absorbed diode-pump power (at 975 nm). The internal conversion efficiency of the laser with respect to the fundamental power entering the enhancement cavity was >63%. The prospects for further improvement in performance with respect to conversion efficiency and output power will be discussed.

Keywords: fiber laser, ytterbium, continuous wave, visible laser, green laser, second harmonic generation

1. INTRODUCTION

High power laser sources emitting in the visible spectral region have a diverse range of applications in areas such as laser processing of materials, projection displays, medicine and sensing. For the continuous-wave (cw) operating regime the most popular approach for generating visible output is via intracavity second harmonic generation in a diode-pumped ‘bulk’ solid-state laser. This approach exploits the relatively low resonator losses and hence high intracavity powers that can be achieved in these lasers to yield high second harmonic conversion efficiency and output powers in multi ten-watt regime [1]. However, scaling to higher powers is rather more challenging due to the effects of heat generation in the laser medium which lead to degradation in beam quality and increased resonator loss. Fiber lasers benefit from a geometry that is relatively immune to the effects of heat generation in the core and hence offer a route to much higher power levels in the near-infrared wavelength regime via the use of cladding-pumped architectures [2], and hence offer the prospect of much higher power levels in the visible regime via nonlinear frequency conversion. Unfortunately, the technique of intracavity second harmonic generation is not well-suited to cladding-pumped fiber lasers, since they have rather high resonator losses. One solution to this problem is to employ the technique of external resonant cavity second harmonic generation. This approach has been successfully applied to cw fiber sources [3], but suffers from the drawback of added complexity since a single-frequency fiber master-oscillator power-amplifier is required and the master-oscillator and/or resonant cavity lengths must be actively stabilized to ensure that the resonance condition is maintained at all times.

In this paper we present an alternative scheme for efficient second harmonic generation in cladding-pumped continuous-wave fiber lasers. Our approach makes use of a simple fiber laser resonator containing an internal resonant enhancement cavity with a nonlinear crystal for second harmonic generation. The fiber laser automatically lases on axial modes which are simultaneously resonant in the enhancement cavity and main cavity. As a result, the intracavity power in the enhancement cavity is increased to many times the cw power that can be extracted from the fiber laser alone, leading to high second harmonic conversion efficiency. In contrast, to external resonant frequency doubling, this approach does not require a single-frequency fiber source and there is no need for active cavity length stabilization since the fiber laser can only lase on axial modes which are resonant in the enhancement cavity. We have applied this technique to a cladding-pumped ytterbium(Yb)-doped fiber laser to achieve efficient nonlinear frequency conversion of near-infrared (fundamental) output at ~1080 nm to the green output at ~540 nm.

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2. EXPERIMENTAL SET-UP AND RESULTS

The experimental configuration (shown in Fig. 1) comprised a double-clad fiber with a polarization-maintaining Yb-doped core in a simple standing-wave resonator. Feedback for lasing was provided by a diffraction grating at one end of the fiber, and by an external cavity containing a resonant enhancement cavity at the opposite end of the fiber. A simple four-mirror ‘bow-tie’ cavity design was employed for the enhancement cavity with a Brewster-angled LiB₃O₅ (LBO) crystal placed in an oven and cut for type I non-critical phase matching. Pump light was supplied by a fiber-coupled diode source at 975 nm and coupled into the end of the Yb-doped fiber adjacent to the diffraction grating. The diffraction grating was used to select the operating wavelength and narrow the emission spectrum to lie within the phase matching bandwidth for second harmonic generation.

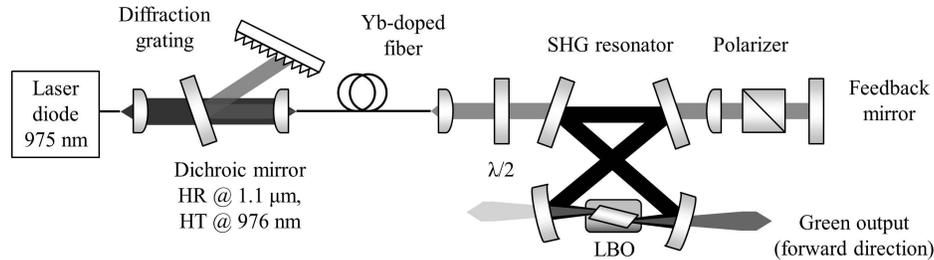


Figure 1. Schematic of the experimental set-up

With this set-up, we obtained 15 W of CW second harmonic output (at 540 nm) in the forward direction (Fig. 1), corresponding to 19 W generated inside the LBO crystal, for 90 W of absorbed diode pump power (at 975 nm). The output power in the reverse direction was <100 mW. The internal conversion efficiency of the laser with respect to the fundamental power entering the enhancement cavity was >63%. The output was linearly-polarized with a beam propagation factor (M^2) <1.25. The laser was tunable over the range of 540-560 nm (for a 20 m long Yb-doped fiber) and over the range 520-550 nm (for a 10 m long fiber) by adjusting the grating angle and the oven temperature to maintain phase matching. The output power stability (rms noise over 100s) was measured to be <0.7%. These preliminary results were obtained with a non-optimal set-up due to limited availability of components. The prospects for further improvement in performance in terms of output power, conversion efficiency and range of operating wavelengths will be discussed.

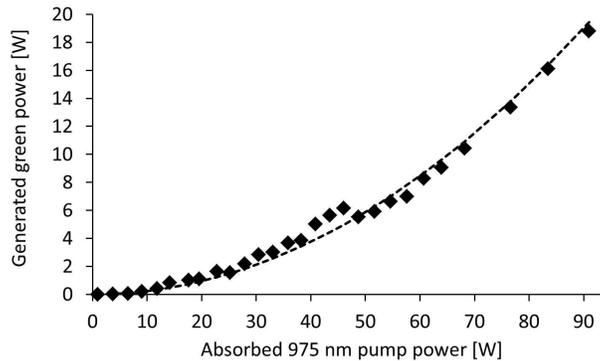


Figure 2. Generated second harmonic power at 540 nm as a function of absorbed diode pump power at 975 nm

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Pump limited 203 W monolithic single frequency fiber amplifier: a two-tone approach

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ABSTRACT

We present high power results of a co-pumped monolithic polarization maintaining (PM) Yb-doped fiber amplifier seeded with a combination of broad and single-frequency laser signals. For the former, a tunable 1035-1045 nm source was used while the latter operated at 1065 nm. This two-tone concept was used in conjunction with externally applied or intrinsically formed thermal gradients to demonstrate at high power combined SBS suppression factors of up to 7 dB in a 7 meter long Nufern 25/400 fiber. Depending on the input parameters (seed powers and wavelength of broadband source) and the thermal gradient, the output power of the single-frequency signal ranged from 80 W to 203 W with slope efficiencies from 70-80%. The 203 W output with a nominal linewidth of 100 kHz was obtained through the application of an external thermal gradient and by seeding the broadband signal at 100 times the power of that of the single-frequency seed. To the best of our knowledge, the 203 W result is the highest reported in the literature for monolithic PM single frequency fiber amplifiers. Furthermore, measurements of the spectral content of the backward light as recorded on an optical spectrum analyzer and a photodiode indicated that we were operating below the SBS threshold. We estimate that, with sufficient pump power and optimized fiber length, approximately 300 W of single-frequency output can be obtained.

Keywords: Yb-doped fiber lasers, stimulated Brillouin scattering, nonlinear optics

Attachments:

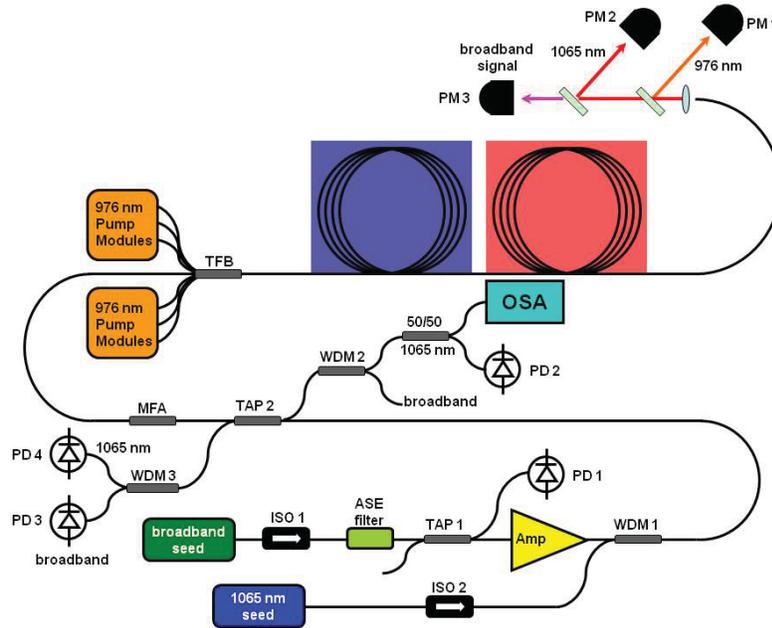


Figure 1 Experimental set-up of monolithic two-tone fiber amplifier system. PD 1, PD 2, PD 3, and PD 4 are photodiodes. ISO 1 and ISO 2 are isolators. PM 1, PM 2, and PM 3 are power meters. The ASE filter is used to suppress noise introduced by the broadband laser in order to allow for seeding with highly skewed ratios.

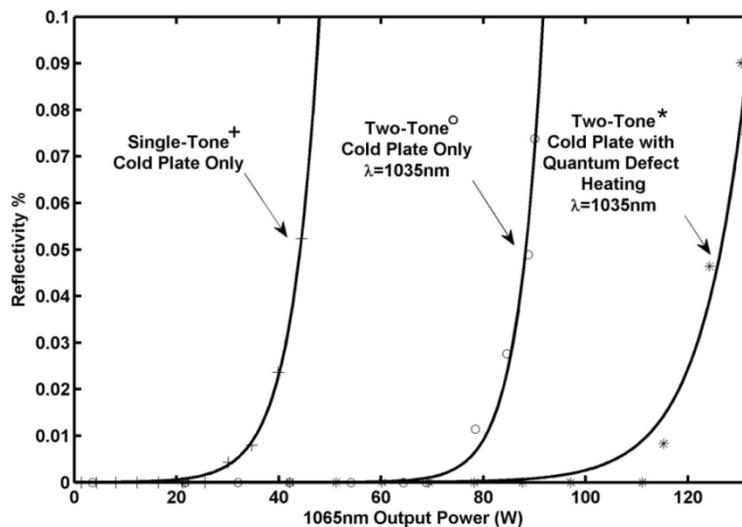


Figure 2 Reflectivity vs. single frequency 1065nm signal output power for a PM monolithic amplifier in different thermal configurations : single tone all on cold spool, two-tone all on cold spool seeded with 1035 nm broadband light , and two-tone with 6 m on cold spool and 1 m left to cool in air under ambient conditions (thus utilizing quantum defect heating). Unlike the

single tone case, the thermal gradient developed through quantum defect heating develops at the output end of the fiber; thus allowing for further SBS suppression.

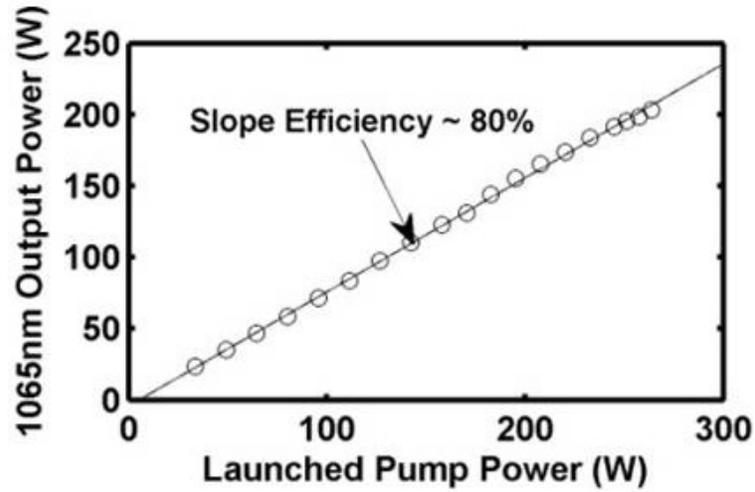


Figure 3 Single-frequency output power vs. launched 976 nm power. The broadband seed operated at ~ 1035 nm. Approximately 6 meters of the fiber were wrapped around a 12°C spool with approximately 1 meter wrapped around an 80°C spool. At maximum available pump power, the output was 203.5 W. At this power, the SBS was below threshold.

