Performance of kW Class Fiber Amplifiers Spanning a Broad Range of Wavelengths: 1028~1100nm

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ABSTRACT

We present results on the amplifier performance and characteristics of Yb-doped Single Mode fiber amplifiers spanning a broad range of wavelengths from 1028 nm to 1100 nm. Both PM and non-PM amplifiers are discussed, with emphasis on the use of polarization controllers in intrinsically non-PM amplifiers to obtain high Polarization Extinction Ratios (PER). In general, outside the 1064nm region, there has been relatively little discussion or work towards developing high power fiber amplifiers for operation at either 1030 nm or 1100 nm with narrow line-width and high brightness, primarily due to amplifier design and architecture issues related to strong re-absorption and amplified spontaneous emission. Here we address key fiber and amplifier design characteristics aimed at mitigating these issues while highlighting performance attributes and challenges for operation near either end of the above defined spectral range.

Keywords: kW fiber amplifier, 1028 nm, 1030 nm, 1100 nm, narrow line-width, single mode, ASE, YDF fiber.

1. INTRODUCTION

Over the last decade fiber amplifiers and fiber lasers have experienced a dramatic increase in output power [1]. Single mode fiber lasers/amplifiers have been demonstrated to operate at 1064 nm to kW power levels at narrow line-width [2, 3] and up to 10 kW with much broader line-width [4]. Ytterbium-doped fibers can theoretically provide continuous-wave (CW) high power output with wavelengths ranging from ~1000 nm to ~1150 nm [5] while maintaining a good beam quality thanks to its large surface to volume ratio, waveguide effect and relatively small quantum defects when pumped by 9xx nm laser diodes. So far, fiber amplifiers in the wavelength range from 1060 nm to 1080 nm have found broad applications in industry, defense and scientific research and are still progressing towards higher power. Applications requiring wavelengths shorter than 1030 nm and above1100 nm are gradually increasing. For shorter wavelengths, the smaller quantum defect enables lower thermal load, higher conversion efficiency, and higher nonlinear effect threshold therefore potentially facilitating higher power operation. Via frequency up-conversion, it will enable high power at visible spectral range down to 515 nm. Also, some medical applications also ask for high power at shorter wavelengths. As for longer wavelengths, frequency up-conversion will enable wavelength into yellow-orange range.

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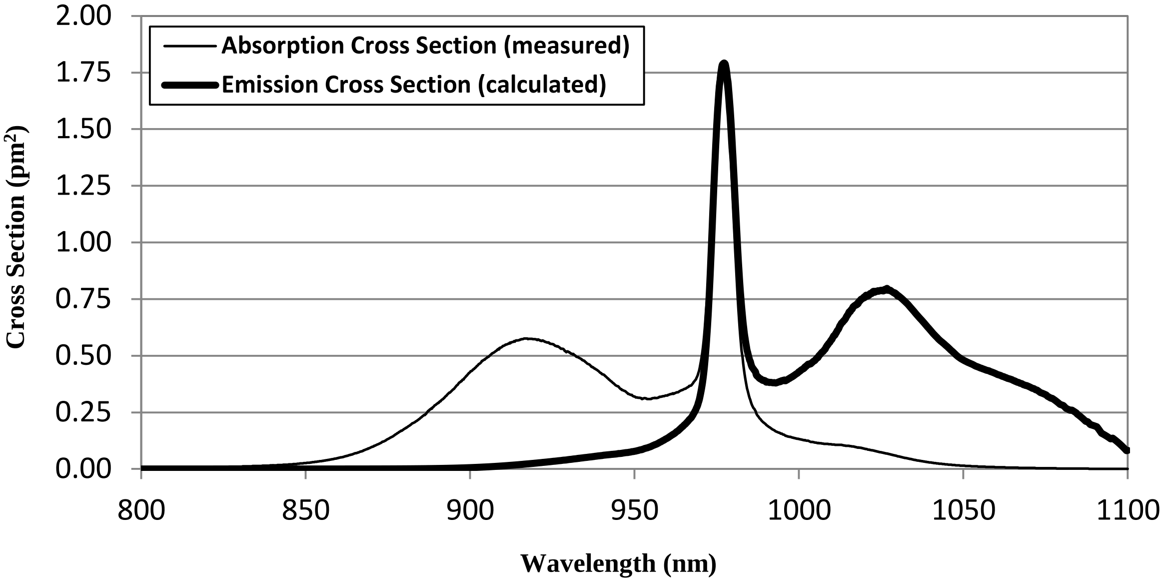


Figure 1. Spectra of absorption and emission cross sections of Yb-doped fiber.

However, due to the dependence of emission/absorption cross sections on wavelength, compared to 1064 nm, high power laser light with wavelengths in the two extremes are relatively difficult to generate. To our understanding, so far the reported highest power achieved with narrow line-width from a fiber laser/amplifier at 1030 nm was no more than 700 W [6, 7]. Although multi-kW CW output power centered at 1100 nm has been generated from fiber lasers recently [8, 9], the line-widths are broad, more than 10 nm. In either case, the Amplified Spontaneous Emission (ASE) has been the primary obstacle to achieve high power. As shown Figure 1 [10], the emission cross section beyond the 976 nm area peaks around 1028 nm and gradually decreases with wavelength. The absorption cross section at 1030 nm is about 8 times higher than that at 1064 nm. This means that the generated signal power at shorter wavelength can act as a pump source for longer wavelength in the ASE content. For longer wavelengths, both absorption and emission cross sections decrease. In this case, re-absorption is no longer an issue, but ASE from its red side joins to compete for power extraction and could be strong because of its much larger emission cross sections therefore limiting high power operation.

Although in both regimes the limiting factor is ASE, the mitigation schemes differ. To address the ASE power buildup while short wavelength signal is desired, the active fiber has to be short enough so that re-absorption will be minimized. The tradeoff, however, is the reduced conversion efficiency. Active fiber that is too short will lead to insufficient absorption of pump light. Thus to maintain reasonable optical-optical conversion efficiencies, optimal active fiber length should be selected.

When the signal wavelength is long, the active fiber length should be long enough so that energy extracted into ASE can be converted into signal along the length of the fiber via re-absorption. The upper limit of fiber length however is nonlinear effects. An approach common to both wavelength extremes is to utilize narrow band-pass filters to block the ASE.

In some applications a polarized output beam is required. In our experiments, we’ve utilized both PM and non-PM fibers to achieve this. The advantages of working with non-PM fibers to obtain polarized beams are its simplicity in volume production, high PER stability and availability of high power components.

2. EXPERIMENTAL SETUP

The setup was similar to our previous experiments [3]. The amplifier consists of a multi-stage pre-amplifier and a high power stage. All of the components are fiber coupled which makes the system more robust and maintenance free. Isolators are used between each amplification stage to prevent unwanted back-reflection. To reduce the ASE levels we utilize 976 nm pump diodes in all amplifier stages. The absorption cross section at 976 nm is about three times higher than that at 915 nm, therefore the active fiber can be about three times shorter for an equivalent amount of absorbed pump light. However, because of its much narrower absorption bandwidth, about 6 nm at 976 nm vs. more than 15 nm at 915 nm, pumping at 976 nm requires more careful temperature control. In our experiments, the diodes were water cooled to maintain the temperature at ~ 23°C. To keep the number of amplification stages small narrow band-pass filters centered at 1029 nm [FWHM ~ ±3nm] were used inter-stage in the pre-amplifier. With these filters the out of band ASE going into the next amplification stage is reduced dramatically so that most of the ASE inside that amp stage is generated from within its active fiber where the amount is controlled by its length.

The amplifier is operated in a co-propagating scheme. Active fibers used in all the three pre-amp stages are Nufern's Yd-doped double clad single mode fiber with low NA. Since the active fiber length is relatively short the pump power absorption is not complete. There is still unabsorbed pump light remaining after each pre-amp stage. To prevent it from propagating into the following components high power pump dumps after the active fiber output are incorporated.

The final power stage consists of a high power beam combiner, which can handle multi-kW power with only 0.2 dB loss. Nufern's Yd-doped large area mode double clad fiber is used as the active gain media in this power stage. It has low NA and relatively low absorption.

3. RESULTS – 1028-1030 nm SEED

The seed source was a non-PM fiber coupled tunable laser which can generate about 40 mW signal power at wavelengths ranging from 1028 nm to 1030 nm. The preamplifier output power was 20W. The amplifier signal output power as a function of launched pump power is shown in Figure 2. When 1614 kW pump power was

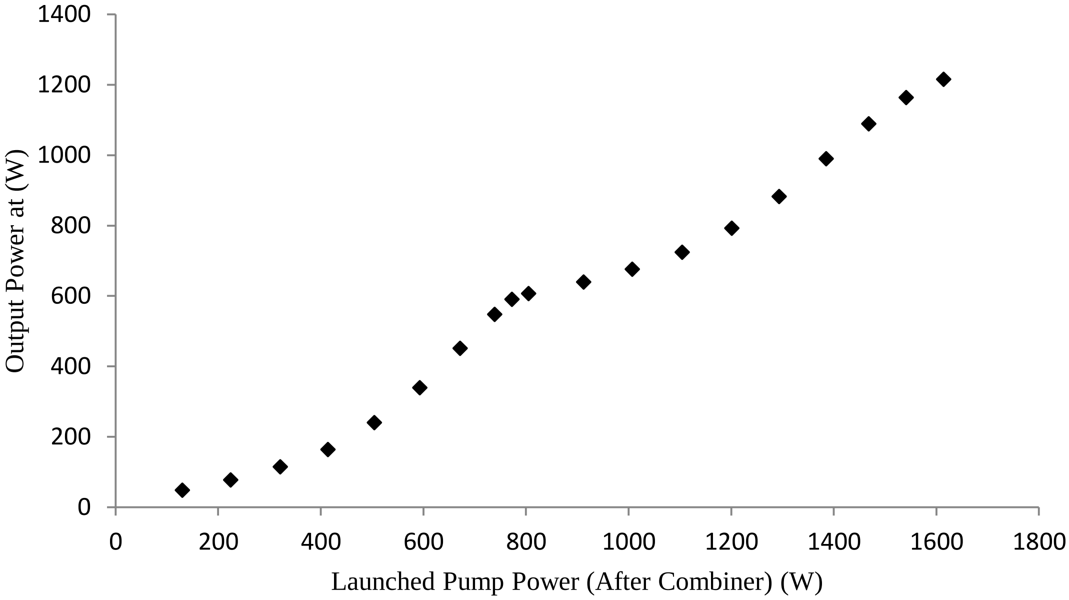
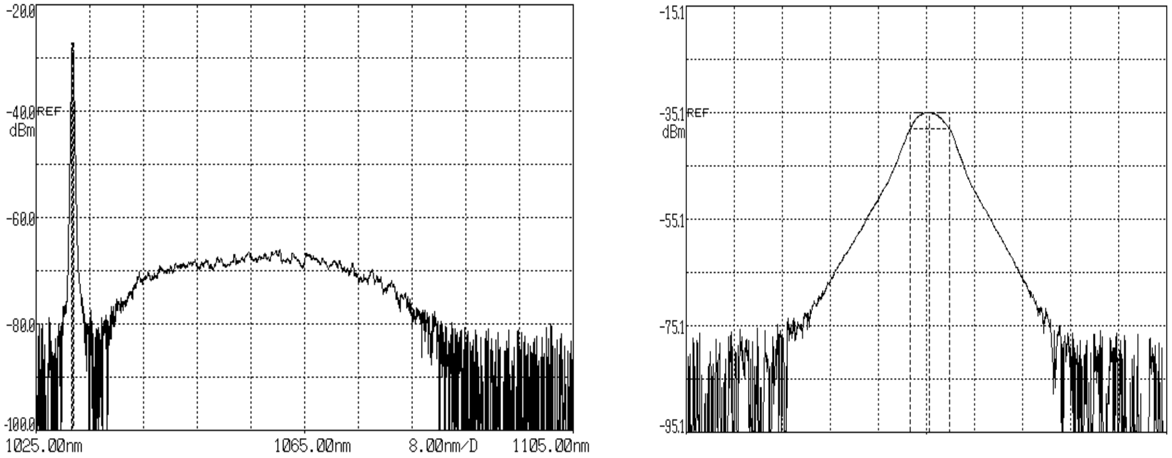


Figure 2. Output power as a function of launched pump power.



(a)

(b)

Figure 3. Forward output spectrum at 1.2 kW (1030 nm). (a) Signal and ASE. (b) Details of the signal.

launched into the final active fiber 1215 W signal at 1028.4 nm was obtained. The optical-to-optical efficiency is about 75%. The unabsorbed pump power (~300 W) was removed by a water-cooled pump dump.

The beam quality was measured by a Thorlabs' M^2 Beam Quality Analysis System using the second moment method (D4σ). M^2 was at about 1.05 over the whole power range. This near diffraction limited output was obtained by appropriately coiling the final stage active fiber.

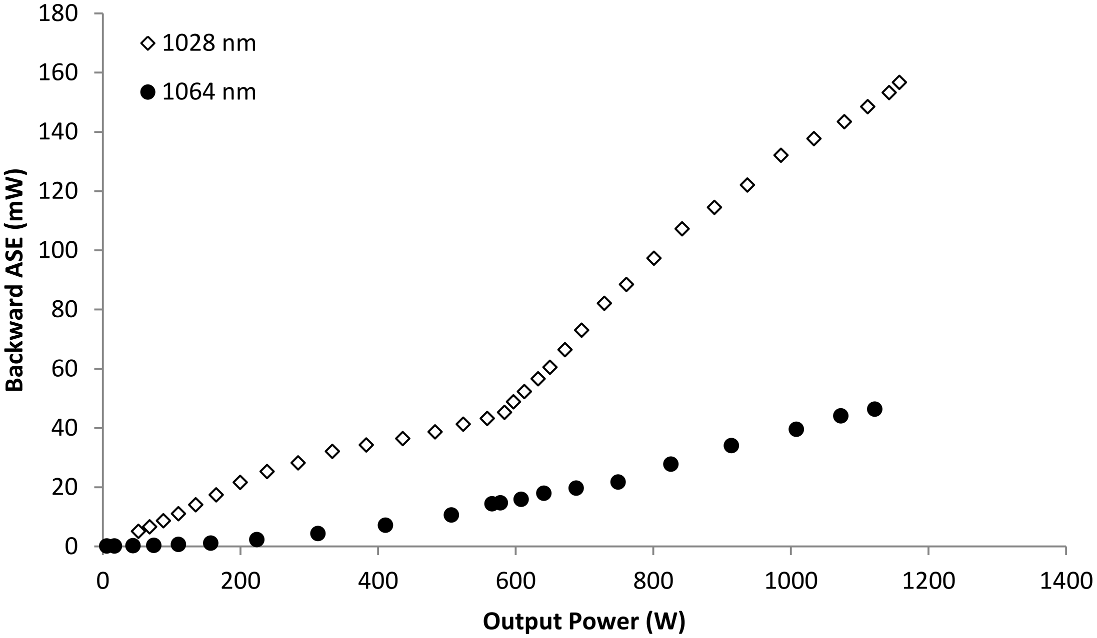


Figure 4. Backward ASE with 1064 nm and 1028 nm seeds.

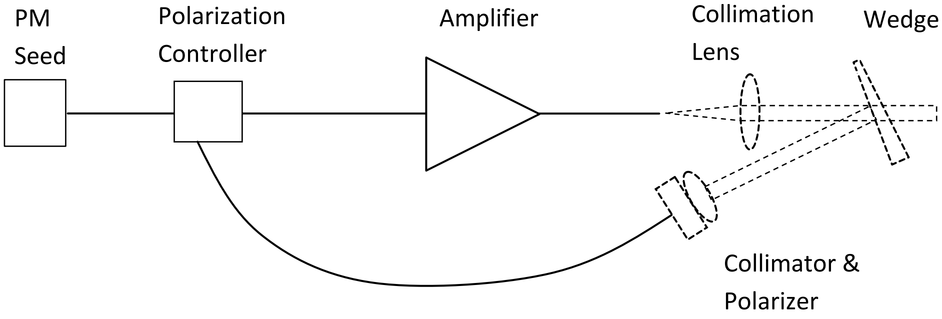


Figure 5. Polarization controller using external feedback.

The forward ASE content was estimated by analyzing the output spectrum [Figure 3]. It was found to account for 1% of the total output power. The backward ASE was measured from a tap located at the pre-amplifier output and is shown in Figure 4. For comparison, the backward ASE when the power stage was seeded with a 1064 nm signal is also shown. The backward ASE at 1028 nm was about 4 times higher than for 1064 nm.

Polarization was maintained with a polarization controller. The polarization control loop was tested as shown in Figure 5. A sample of the output signal was picked up by a wedge and was sent back to the polarizer controller [General Photonics POS-002]. The measured PER was about 16 dB.

4. RESULTS – 1100nm SEED

The 1100 nm amplifier utilized PM fibers to maintain an output linear polarization. The amplifier architecture was similar to that of the 1028/1030 nm system, where a multi-stage pre-amp amplified a 5 mW seed to about 10 W.

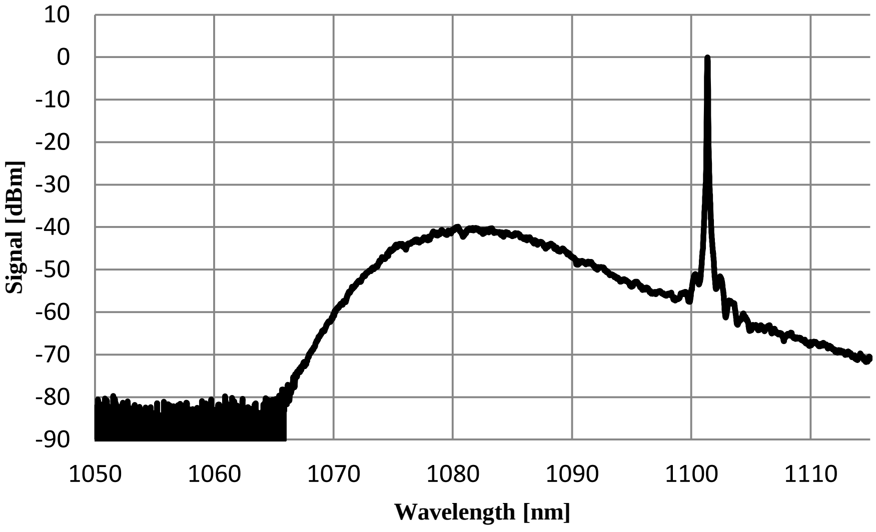


Figure 6. Output spectrum of 1100 amplifier.

Another major difference between the two systems was the length of active fibers. The preamplifier stage required extra fiber length to reduce the ASE content due to re-absorption. For a similar purpose, the active fiber length of the final power stage was also significantly long to maximize the output power while keeping the ASE low. However, due to the long length of the active fiber, SBS started to build up and eventually limited the available output power. The maximal power achieved from this amplifier was 304 W pumped with about 480 W laser diodes at wavelength around 915 nm. The measured M2 was 1.13 and the PER was about 15 dB. Figure 6 shows the forward spectrum of the amplifier at full power.

5. CONCLUSION

We have demonstrated an all fiber amplifier that can generate high brightness, narrow line-width with more than 1.2 kW output power at 1028/1030 nm, a wavelength in the shorter end of the emission spectrum of Ytterbium-doped fiber, and an all fiber amplifier running towards its longer end which can generate more than 300 W at 1100 nm. In the future, the availability of higher power components, optimization of the amplifier architecture and fiber absorption should allow better conversion efficiency and yield to multi-kilowatts power.

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