High Peak Power Single-mode Amplification Using Highly Doped Double Cladding Ytterbium Phosphosilicate Fiber

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Abstract: 50 kW peak power single-mode amplification with a short and highly doped phosphosilicate double cladding fiber pumped at 976 nm is demonstrated using a simple MOPA configuration operated in highly saturated energy regime
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1. Introduction

Many scientific and industrial applications require high peak power laser pulses at 1 µm. Ytterbium doped fiber amplifiers are interesting for such application due to their compactness, efficiency and good beam quality. But achieving high peak is challenging with fibers due to the difficulty of enlarging the mode area to reduce non-linear effects while maintaining a high beam quality. Several large mode area solutions exist such as using photonics crystal fibers or leaky channel fibers [1, 2]. While those approaches can achieve very large peak power, they are expensive to manufacture, require free space coupling, and are limited in term of bending radius.

Instead of maximizing the mode area, another approach to mitigate non-linear effects is to minimize the fiber length. This can be achieved with highly doped fibers using a high core to cladding ratio to maximize the pump absorption. Double cladding ytterbium phosphosilicate fibers are a good candidate due to their high doping level achievable without photodarkening [3], low background loss and compatibility with all silica components readily available. Simple and low cost configurations can then be used to obtain high peak power.

Wavelength locked pumps at 976 nm are now available with higher brightness and lower cost, which maximizes the pump absorption of ytterbium amplifier. Scaling the core diameter to increase the pump absorption can be done without degrading the beam quality simply by proper injection of the LP_{01} mode into the fiber [4]. Such combination of pumps and fiber designs allows very short length amplifier below the 1 meter length in order to achieve high peak power output.

2. Configuration

A simple and standard master oscillator main amplifier (MOPA) configuration, as shown on Figure 1, was used to conduct the experiment. A 1064 nm seed diode was current modulated to produce pulses of 400 ns width with 10 kHz repetition rate, which gave an average power of 3 mW. One pre-amplifier made of a phosphosilicate 9µm core diameter fiber was used to pre-amplify the signal to 350 mW average power. Isolators were spliced before and after the pre-amplifier to block any backward feedback. All components used for the seed and pre-amplifier were pigtailed in Corning single-mode HI1060 fiber.

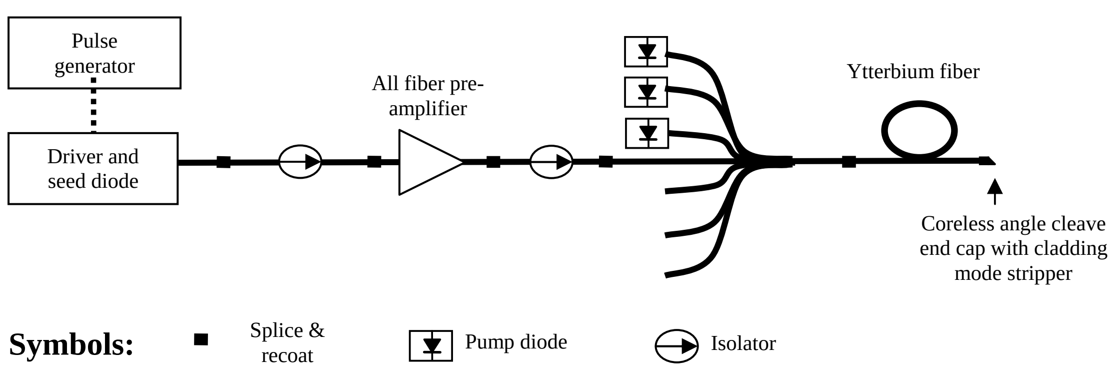

Fig. 1. MOPA configuration used to conduct the high peak power experiment

The power amplifier was made with a 20/128 µm core/cladding diameter phosphosilicate ytterbium fiber. The measured small signal pump absorption at 976 nm of such fiber was 47 dB/m, so only 50 cm of fiber length was used for the amplifier. Such fiber is photodarkening free due to the phosphorous co-doping even if the absorption value is very high [3]. A matched LMA single-mode fiber was used to inject the LP_{01} mode in the doped fiber (CorActive's DCF-Un-20/125M). A coreless end cap was spliced directly at the output of the ytterbium fiber to avoid surface damage. A cladding mode stripper was also used at the end to remove most of the residual cladding light. The fiber was co-pumped with a 976 nm wavelength locked 25W diode coupled in a 105µm/0.22NA core diameter/NA fiber from the company BWT Beijing. Those pumps have a stable linewidth smaller than 0.5 nm locked at 976 nm whatever the drive current to pump consistently the maximum Yb absorption peak.

3. Pump absorption

Minimizing the Yb fiber length of the power amplifier is the key point of the experiment to achieve high peak power, so the pump absorption was investigated carefully. The effective pump absorption at 976 nm was measured doing cut-backs of the 20/128 Yb phosphosilicate fiber in the amplifier configuration. The results are shown in Figure 2 on the left. The effective absorption is lower than the cladding small signal absorption of 47 dB/m. A simulation of the pump absorption using a typical fiber amplifier modeling adapted for Yb was done [5]; the results are shown in Figure 2 on the right.

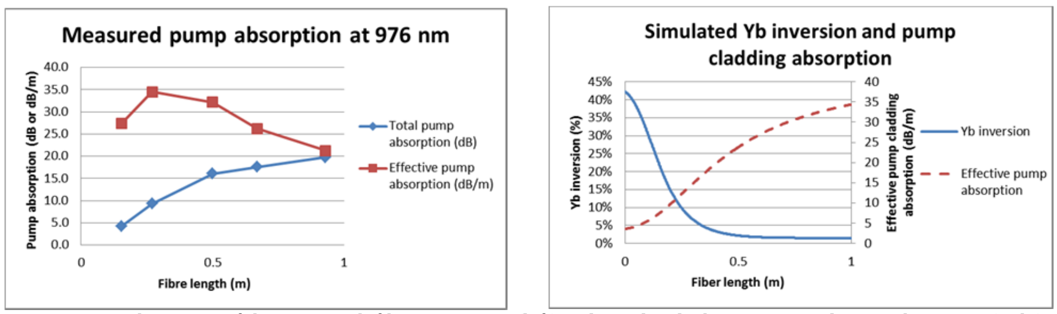

Fig. 2. Pump absorption of the 20/128 Yb fiber at 976 nm. (left) and simulated Yb inversion and pump absorption (right)

The pump absorption rate was clearly reduced in the first half meter due to the high inversion level achieved in the Yb fiber; the amplifier is therefore operated at the pump bleaching limit of the fiber. Even if pump bleaching occurs, the measured pump absorption showed that only 50 cm of fiber is required to absorb 16 dB of pump at 976 nm. The cavity could be shortened to 30 cm if 10 dB of pump absorption was aimed to further minimize non-linear effects. The pump absorption would be 15% higher if the pump wavelength was shifted to 975 nm, which is the peak absorption of phosphosilicate Yb fiber. The reduced pump absorption measured for long fiber length greater than 50 cm is due to helical rays [6], which were not taken into account in the simulation.

4. High peak power output results

Using 50 cm of 20/128 Yb phosphosilicate fiber, or 15 dB of pump absorption at 976 nm, a peak power of 50 kW was obtained at 10 kHz with the two stage MOPA design. The average output power reached 10W at 1064 nm using 18 W of pump power.The output temporal profile and spectrum are shown in Figure 3. The main amplifier was operated well above its saturation energy, which gives a very high peak power at the rising edge of the pulse [3]. This phenomenon is used to achieve high peak power easily with only two amplifiers. An input pulse width of 400 ns generated enough average power to avoid adding a third amplifier, while the final effective pulse width is reduced to 20 ns to get the high output peak power.

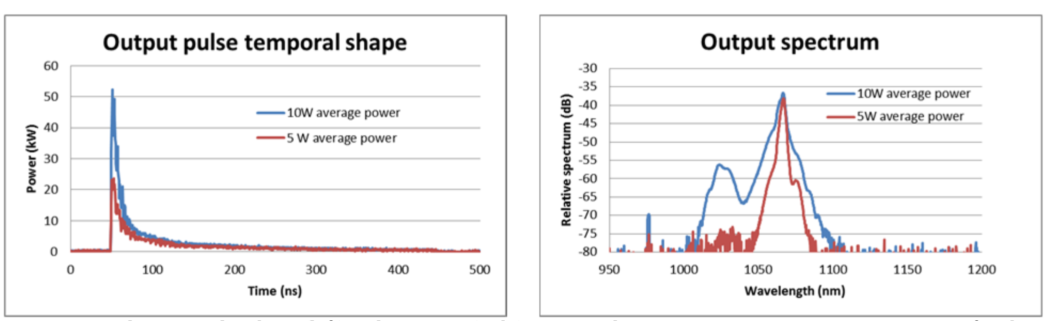

Fig.3.Temporal output pulse shape (left) and spectrum (right) at 5W and 10W average power at a repetition rate of 10 kHz

The output spectrum showed no sign of detrimental non-linear effects: no stimulated Raman scattering (SRS) was observed at 1115 nm and only a slight spectral enlargement of the main signal bandwidth at 1064 nm was measured due to self-phase modulation. Therefore much higher peak power could have been reached by this configuration. Operating the power amplifier with some ASE generated surely contributed to the free SRS output at 1115 nm [7].

The main limitation in scaling the output power was amplified spontaneous emission (ASE) at 1030 nm due to the high energy output reached by the amplifier. At 10W output, the spectrum was still clean with an extinction ratio greater than 20 dB between the 1030 nm ASE and main signal peak at 1064 nm. But going to higher power only increased the ASE level and lead to self-pulsing that destroyed the main amplifier gain fiber, though a backward Brillouin pulse is also suspected due to the narrow modes of the seed diode [3]. A higher peak power could be reached with this configuration by optimizing the input pulse width, repetition rate and the gain at each amplifier stage.

The beam quality of the output beam was measured to be quasi single-mode with M^2 values down to 1.15. This was achieved by injecting the LP_{01} in the doped fiber using a single-mode LMA fiber. The doped fiber temperature elevation was 30°C at maximum power without any cooling: the fiber was simply held in the air in ambient temperature of 25°C. This temperature elevation is reduced by half just by coiling the fiber around an aluminum mandrel. This low heating is due to the low quantum defect between the 976 nm pump and 1064 nm signal and the low background loss of the fiber. Higher pumping could be done without reaching the 80°C safe operation limit recommended for the coating. Therefore the very high absorption design does not bring any temperature limitation at these power levels.

No delivery fiber was incorporated in the design: high peak power cannot be tranported efficiently in an optical fiber without generating non-linear effects. But this is not restrictive when using such amplifier design since the fibers used can be coiled to radii down to 30 mm. Therefore it is possible to put the main amplifier module alone in a small box that is placed directly at application. The output of the gain fiber is then coupled directly to free-space optics.

5. Conclusion

An output peak power of 50 kW was reached using a simple two stage fiber amplifier design seeded with a current modulated diode. Using a 20/128 µm core/cladding highly doped phosphosilicate fiber, only 50 cm of fiber absorbed 15 dB of a wavelength locked pump at 976 nm. It was shown that such high pump absorption brought the doped fiber to a high inversion level that bleached the pump absorption. Operating the main amplifier in a saturated regime shortened the pulsewidth enough to reach high peak power, while the generated pulse from the diode was long enough to avoid adding another pre-amplifier. The output spectrum showed no detrimental non-linear effects, only small ASE at 1030 nm was measured due to the high output energy reached by the amplifier. Higher peak power could be obtained with proper optimization of the operating condition of the diodes and gain of each amplifier stage.

6. References

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