3 mJ All-Fiber MOPA with a Short-Length Highly Er$^{3+}$-doped Phosphate Fiber

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Abstract—A very large mode-area 2 wt% erbium-doped double-clad phosphate fiber with a core diameter of 60 µm and core numerical aperture of 0.03 was fabricated and used for the last stage amplifier of an all-fiber pulsed laser master-oscillator power amplifier (MOPA) at 1550 nm. The Er$^{3+}$ double-clad phosphate fiber has a cladding-core ratio of 2.17 and a V number of 3.6 at 1550 nm. 3 mJ pulses with 21.5 ns duration were obtained with Gaussian-like spatial beam profile with only a 75 cm long phosphate gain fiber.

Index Terms—Erbium-doped fiber amplifiers, Optical Fibers, Optical Pulses

I. INTRODUCTION

HIGH energy and high peak-power pulsed lasers have seen significant development because of their potential applications in long-distance sensing [1]. Solid state lasers have been able to produce the highest pulse energies, but their size, cost and alignment sensitivity constrain their use in many applications where compact and robust laser systems are required. Compared to solid-state lasers, fiber lasers have the advantages of high efficiency, outstanding heat dissipation, excellent beam quality and can be developed in a compact and robust all-fiber format. Although many of these fiber sources have been developed for coherent sensing, there is also interest in developing sources with low-temporal coherence to reduce the impact of speckle in incoherent time-of-flight detection systems [2]–[4]. In this paper, an all-fiber laser system with coherence length as low as 76 µm was reported.

Pulsed erbium (Er$^{3+}$) doped fiber lasers are attractive for long-distance applications due to their eye-safe emission in the 1.5 µm wavelength region and the availability of low-cost and small size telecommunication fiber components. Laser sources with high energy and high peak power are in great demand [5]. In previous work, milli-joule level pulses and high peak powers have been achieved with very large mode area (VLMA) Er$^{3+}$-doped fiber amplifiers [6]–[9]. Up to 2.6 mJ was demonstrated with a few-mode laser [6] and up to 1 mJ was demonstrated with near single-mode performance [8]. However, these systems rely on very long (>100 ns) pulse durations to achieve high-pulse energy [6]–[8]. An all-fiber Er$^{3+}$ amplifier generating 20 ns pulses with pulse energy of 8 mJ and over 200 kW peak power has been demonstrated [9]. However, this laser used a 14 m Er$^{3+}$-doped highly multimode (V number ~ 20) fiber with a non-uniformly doped core of 100 µm diameter and 0.1 numerical aperture (NA), which lead to very poor beam quality (a ring-shaped beam profile) that cannot be used for most long-distance sensing applications. In this paper, we report an all-fiber laser system using a few-mode highly Er$^{3+}$-doped phosphate fiber with core diameter of 60 µm and NA of 0.03 (V number ~ 3.6) for the last stage amplifier, which generates 3 mJ, 21.5 ns pulses with peak power > 100 kW and with a Gaussian-like beam profile.

It is challenging to generate high-pulse energy with short pulses in fiber amplifiers because of significant nonlinear material response. Self-phase modulation (SPM) and modulation-instability (MI) in Er$^{3+}$ lasers can be limiting factors in high peak power lasers [10], [11]. These nonlinearities are hard to avoid in Er$^{3+}$ amplifiers due to the long gain fibers that are generally needed to generate large gain. Sensitizing Er$^{3+}$-doped fibers with Yb$^{3+}$ is an effective method to reduce the required gain fiber length in cladding pumped fiber lasers but is constrained by the parasitic lasing of Yb$^{3+}$ at 1 µm which also compromises their eye-safe emission [11]. Instead, Er$^{3+}$-doped fiber lasers should use cladding-pumped Yb$^{3+}$-free fibers with small cladding-core ratios because of the readily available high-power multi-mode diode pump lasers at 980 nm and the highly promising development of high-power multi-mode diode pumps at 1480 nm. Additionally, to realize an all-fiber high-energy short-pulsed laser at 1.5 µm, it is advantageous to increase the doping concentration of the glass host to shorten the gain fiber.

Phosphate fibers can be doped at very high concentrations which has enabled highly efficient cladding-pumped amplifiers.
with tens of centimeter fiber lengths [12], making them a good candidate for high-energy short pulse lasers. In this work, we present an all-fiber master oscillator power amplifier (MOPA) with a VLMA highly Er\(^3\)+-doped phosphate fiber. The fiber has a cladding-core ratio of 2.17, the lowest demonstrated for a millijoule level Er\(^3\)+-doped amplifier, which creates a large mode field area while retaining efficient pump absorption. A gain fiber of only 75 cm was used for the final amplifier stage. The short fiber length in this amplifier allowed for over 13 dB gain in the final stage with very little additional spectral broadening. The high energy and short pulse output from this laser with moderate beam quality make this system an effective source for speckle-free long-range sensing.

II. EXPERIMENTAL METHODS

The diagram of the experimental setup for the VLMA Er\(^3\)+-doped phosphate fiber amplifier is shown in Fig. 1. A commercial continuous-wave (CW) Fabry-Perot laser diode (Thorlabs, FPL1009S) with a maximum output power of 100 mW over a spectral bandwidth of ~10 nm (1550 - 1560 nm), corresponding to a coherence length of ~76 µm, was used as the seed laser. Nanosecond optical pulses with repetition rates from 5 kHz to 20 kHz were generated with an electro-optical modulator (EOM) (IXBlue MX-LN-20) driven with an arbitrary waveform generator (Keysight, 33612A).

![Diagram of the high energy laser system at 1.55 µm.](image)

The pre-amplifiers include a core-pumped Er\(^3\)+-doped silica fiber amplifier and two cladding-pumped Er\(^3\)+/Yb\(^3\)+ co-doped silica fiber amplifiers, which amplified the nanosecond pulse energy to over 200 µJ. The output pulse energy of each of the pre-amplifier stages was limited by amplified spontaneous emission at 1536 nm. The optimal average output power and pulse energy after the third amplifier stage depended on the repetition rate of the laser pulses. For lower repetition rates interpulse ASE was always much stronger and thus the maximum pump powers for the two cladding-pumped fiber amplifiers needed to be reduced to lower the ASE power entering the final Er\(^3\)+-doped phosphate fiber amplifier. For the highest pulse energies, measured at a repetition rate of 5 kHz in this experiment, the average power of the signal laser after the third amplifier stage was set to 0.7 W, corresponding to an input pulse energy of 140 µJ to the final amplifier stage.

A singly Er\(^3\)+-doped double-clad phosphate fiber was fabricated with the rod-in-tube technique as the gain fiber for the final amplifier stage. The microscopic image of this fiber is shown in the inset of Fig. 1. The fiber core, doped with 2 wt% Er\(^3\)+, has a diameter of 60 µm and a numerical aperture (NA) of about 0.03, corresponding to a V number of ~3.6 at 1550 nm. The background loss of the Er\(^3\)+-doped phosphate fiber is 0.09 dB/cm. The mode area of the fundamental mode is 2150 µm\(^2\). This fiber has an inner cladding with a 130 µm diameter and a NA of 0.45, enabling high brightness cladding pumping at 980 nm with high pump absorption due to the small cladding-core ratio. To enhance the pump absorption, two low index rods were placed in the inner cladding to perturb the propagation of skew rays that usually do not pass through the fiber core to be absorbed. The small signal cladding absorption of the fiber was 6 dB/m.

The final amplifier stage was tested with 25 cm, 50 cm and 75 cm lengths of Er\(^3\)+-doped phosphate gain fiber. Two high-power CW laser diodes at 980 nm were used to pump the gain fiber. The signal and pump light were combined by a (2+1)x1 pump signal combiner. The double-clad fiber at the output of the pump signal combiner had a core diameter of 20 µm and an inner cladding diameter of 130 µm, which was spliced to the phosphate gain fiber with an asymmetric splice technique [13]. This pump-signal combiner was used because the 130 µm cladding matched the inner-cladding diameter of the Er\(^3\)+-doped phosphate gain fiber.

The large quantum defect from pumping Er\(^3\)+-doped fibers at 980 nm can lead to significant heating of the fiber. To manage the heat, the fiber was placed on a water-cooled heat sink. The output end of the Er\(^3\)+-doped phosphate fiber was angle cleaved to suppress the Fresnel reflection and no endcap was used at the phosphate fiber end-facet.

III. RESULTS AND DISCUSSION

The final amplifier stage was measured at 5 kHz, 10 kHz, and 20 kHz repetition rates. The output average power (Fig. 2(a)) and pulse energy (Fig. 2(b)) was measured with a thermal power meter (Newport, 818T-10 / 818T-150) and a pulse energy meter (Ophir, PE10-C) respectively. Lowering the repetition rate lead to a small decrease in the efficiency of the amplifier in average power output (28.8% slope efficiency at 20 kHz and 25% slope efficiency at 5 kHz). However, the increase in stored energy in the gain fiber lead to an increase in pulse energy at lower repetition rates. A maximum pulse energy of 3 mJ was reached at a repetition rate of 5 kHz with a total pump power of 91.5 W. Above 91.5 W the gain of the pulse energy saturated. This saturation effect is shown by the divergence between the pulse energy measured with the pulse energy meter and the estimated pulse energy calculated from the average power measurement and the repetition rate of the laser, as shown in the dotted lines of Fig. 2(b) The saturation of the pulse energy occurs when significant energy stored in the gain fiber
is removed by interpulse ASE. This effect is observed in optical spectral measurements of the amplifier (Fig. 3, inset) where the ASE peak at 1536 nm begins to grow exponentially at the point that saturation begins. At a repetition rate of 20 kHz the amplifier did not exhibit pulse energy saturation. At this repetition rate the pulse energy was limited by the availability of power from the pump laser diodes. Between these two repetition rates, at 10 kHz, the pulse energy from the amplifier begins to saturate from ASE near the maximum pump power from the diodes, indicating that ASE saturation point occurs at high pump powers when the repetition rate is increased, similar to what has been observed in other work [9]. The saturation of the pulse energy cannot be attributed to saturation of pump absorption because no exponential increase in the residual pump power was observed at and above saturation [6].

The optical spectrum of the final amplifier stage operating at a repetition rate of 5 kHz with 3 mJ output is shown in Fig. 3 along with the corresponding pre-amplifier spectrum at 140 µJ which seeded the final amplifier. The pre-amplifier spectrum at low pulse energy (28 µJ) is shown for comparison. Clearly, the most significant spectral broadening occurs prior to the final amplifier due to the strong nonlinear effects in the pre-amplifiers, including MI [10], [14] and Raman scattering [15], in which several meters of Er³⁺/Yb³⁺ co-doped double-clad silica fibers and several meters of passive fiber pigtails from fiber components were used. Due to the VLMA of the fiber and only 0.75 m of the gain fiber at maximum pulse energy, the final amplifier stage adds significantly less spectral broadening while still providing over 13 dB of signal gain. The spectral broadening in this all-fiber laser system can be further mitigated by replacing the Er³⁺/Yb³⁺ co-doped silica fibers with shorter Er³⁺/Yb³⁺ co-doped phosphate fibers and shortening the passive fibers of the fiber components.

The pulse shape at the output of the amplifier was measured with a fast detector (Electro-Optics Technology, ET-5000) at repetition rate of 5 kHz and a pulse energy of 3 mJ, as shown in Figure 4. The pulse shape out of the pre-amplifiers (140 µJ) and the pulse shape measured after the EOM are also shown for comparison. Due to the gain depletion in fiber amplifiers, the

![Fig. 3. Optical spectra of the 3 mJ output (black, solid), pre-amplifier output at 140 µJ that was input to the final amplifier (blue, dashed), and pre-amplifier output at 28 µJ (orange, dotted). Inset: Normalized spectral measurements of the output ASE peak at 1536 nm before saturation (2.3 mJ, red, dotted) as saturation begins (2.8 mJ, green, dashed) and at maximum pulse energy (3 mJ, black, solid).](image-url)
front portion of the optical pulse experienced higher gain than the rear portion, resulting in an amplified pulse with a very sharp leading edge and significantly reduced pulse width. To compensate for this pulse distortion and to achieve a high pulse energy with a short pulse-duration, an initial pulse shape with a slowly increasing front edge and a peak close to the rear edge was used.

The pulse width of the initial signal pulse extends over 60 ns but with a full-width half-maximum (FWHM) of 38 ns. After the preamplifiers, due to the gain depletion of the laser pulse in the amplifier, the pulse width of the signal pulses was reduced. The FWHM after the pre-amplifiers was 28.9 ns. After the final stage amplifier, the peak of the pulse was further shifted to its leading edge and the pulse width was further reduced. The 3 mJ output pulses at a repetition rate of 5 kHz had a FWHM of 21.5 ns.

The beam quality of the output pulses of the final amplifier stage was measured with a scanning slit beam profiler (DataRay, BeamMap2) and is shown in Fig. 5. The beam qualities in x and y directions were measured to be 3.8 and 3.6 respectively. It should be noted that the transition from the 20 µm core silica pump/signal combiner to the 60 µm core phosphate fiber was very non-adiabatic and likely had a detrimental effect on the beam quality of the output laser. The beam quality of this all-fiber laser can be improved by further optimizing the splice from the 20 µm core double-clad silica fiber and by using a mode-field adaptor between the two double-clad fibers.

IV. CONCLUSION

In conclusion we have demonstrated a short-length VLMA highly doped Er3+-doped cladding pumped phosphate fiber amplifier for pulsed eye-safe lasers in the 1.55 wavelength region. A maximum pulse energy of 3 mJ in a 21.5 ns pulse at a repetition rate of 5 kHz was obtained with a pump power of 92 W at 980 nm, making this a useful source for speckle-free long-distance sensing applications that require high energy in a short time window.

Fig. 4. Normalized pulse shapes of the 3 mJ output (black, solid) pre-amplifier output at 140 µJ that was input to the final amplifier (blue, dashed) and the initial pulse shape of the seed laser (green, dotted) measured after the EOM.

Fig. 5. Beam quality measurement result in the x (solid circles) and y (solid squares) directions. Solid lines show the Gaussian fit to the measured data and the calculated M2 beam quality factor for non-diffraction limited Gaussian beams in both x and y directions. (inset) Beam profile of the laser at the focus.

REFERENCES