

Millijoule-level Ultra-Large Core Ytterbium-Doped Pulsed Fiber Amplifier Operating at 980 nm

Pablo G. Rojas Hernandez, Shankar Pidishety, Mohammad Belal, and Johan Nilsson

Abstract—We report a record-high 5.5-mJ amplified pulse energy at 980 nm, achieving 0.55 kW peak power using a 1-meter long ultra-large-mode-area (290 μm core) ytterbium fiber in a co-directional, amplifier configuration. Pumped at 915 nm and seeded by a modulated 980-nm laser diode. We provide a detailed fiber spectroscopy analysis, optimizing key parameters—such as seed and pump repetition rates to mitigate thermal load and other detrimental effects (e.g., re-absorption), enabling high-energy output. The amplifier's performance highlights its applications for high-brightness ultraviolet and visible light generation, and as an efficient pump for erbium-doped fiber systems, advancing their performances in fluorescence imaging, marine engineering and biophotonics. To the best of our knowledge, the achieved output energy of 5.5 mJ is the highest reported to date in an ytterbium-doped-fiber amplifier at 980-nm, while offering simpler fabrication, configuration and enhanced compatibility compared to other fiber systems at similar wavelengths.

Index Terms— Fiber optics, Ytterbium-doped fiber, fiber amplifiers, high energy pulses

I. INTRODUCTION

Ytterbium-doped fiber amplifiers (YDFAs) and lasers are renowned for their superb efficiency and power-scalability [1] and have reached over 100-mJ of pulse energy and MW-level of peak power [2] in the pulsed regime. However, although ytterbium ions (Yb^{3+}) have an emission peak at around 980 nm, these results are generally obtained at wavelengths in the range 1030-1100 nm. By contrast, reabsorption at 980 nm in combination with competing quasi-4-level emission at the longer wavelengths makes cladding pumping difficult [3] and scaling of the average power at 980 nm much more limited [4-6]. In addition, pulse-energy scaling is hampered by the low saturation fluence at 980 nm ($\sim 0.05 \mu\text{J}/\mu\text{m}^2$ at the 980-nm emission peak in aluminosilicate, compared to, e.g., $\sim 0.2 \mu\text{J}/\mu\text{m}^2$ at the secondary peak at 1030-1040 nm, and $\sim 0.4 \mu\text{J}/\mu\text{m}^2$ at 1064 nm). This is a consequence of the large peak absorption and emission cross-sections. Therefore, to date, pulsed sources based on ytterbium-doped fibers (YDFs) have been limited in power to 78 W with 0.4-mJ pulse energy at 980 nm [7, 8]. Nearly 1 mJ could be reached at lower pulse repetition frequencies (PRF), but then with large levels of amplified spontaneous emission (ASE). Additionally, experimental studies of YDFAs have reached record highs of

500-W level in the continuous-wave (CW) regime and up to 63 kW peak powers in femtosecond pulses near 980 nm [4-10]. Some of these results were achieved using large-mode area, YDFAs, or rod-type, photonic crystal fiber designs, alongside end and side-pumped diode lasers (DLs), Q-switched systems and double-clad YDFs. Although large-core, their design allowed for low-numerical aperture (NA) enabling high beam quality (e.g., $M^2 \approx 1.3$), their efficiency significantly limited by in-band ASE [5, 8, 10]. To the best of our knowledge, all reported high-power YDF laser systems that operate close to 980 nm have used microstructuring or air:silica fibers [11], requiring precise and complex fabrication or configuration which limits their potential and further studies.

Recently, advancements in large-core fibers, such as extra-large-mode-area (XLMA) fibers with core diameters up to 300 μm , have opened new possibilities for scaling pulse energy [10], in simple and robust configurations. While these fibers have been primarily utilized at wavelengths between 1000-1100 nm for applications like materials processing, the precise wavelengths are often not critical in such cases [8, 12]. In contrast, 980 nm is more challenging but attractive for offering temporal and spatial capabilities beyond those of 980-nm DLs. These properties are important, e.g., for pulse-pumping of nonlinear devices such as frequency-doublers and nonlinear fiber amplifiers, as well as of rare earth-doped fiber devices with short excited-state lifetimes (e.g., due to concentration quenching) [12-14]. In this article, we leverage an XLMA YDFA with a 290- μm diameter aluminosilicate core to amplify 980-nm pulses at low PRF to high energies. The amplifier is core-pumped by a DL at 915 nm, with pulses seeded by a 980-nm DL. The XLMA YDF, combined with the high brightness of the 915-nm DL pump, facilitates efficient pump-to-signal energy transfer, high absorption, and enhanced amplification performance at the challenging 980-nm wavelength. To the best of our knowledge, this work demonstrates the highest pulse energy reported to date at 980 nm in an XLMA YDFA system, highlighting the potential of such lasers for their applications in fluorescence imaging, marine engineering and biophotonics.

II. GAIN FIBER ANALYSIS: XLMA-YTF-300/400/480

We consider the commercial fiber Nufern, XLMA-YTF-300/400/480- μm , 0.11-NA Yb:aluminosilicate circular core

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measured to 300- μm diameter (area 0.0661 mm^2 , supporting ~ 2630 LP-modes at 977 nm), inside an octagonal first (inner) cladding with a 400- μm flat-to-flat diameter (enclosed area 0.133 mm^2 , 0.23 NA) and a 2nd cladding of 480- μm flat-to-flat diameter (enclosed area 0.191 mm^2). This was coated by a low-index polymer and has a NA of 0.46 relative to the first cladding and 0.40 relative to the second cladding. Thus, light can propagate throughout the glass structure, but here we launch the pump light so that it is confined to the core. The large core area of the fiber helps to compensate for the low saturation fluence at the 980 nm wavelength, at the expense of beam quality. Equations (Eq.) (1) and (2) relate the extracted energy from a fiber amplifier to the gain modulation G_{mod}^{Np} it induces [14]:

$$E_{extr} = U_{sat} * G_{mod}^{Np} \quad (1)$$

$$U_{sat} = A * F_{sat} = A * (h\nu / (\sigma_{ems} + \sigma_{abs})) \quad (2)$$

Thus, the extractable energy E_{extr} is determined by the product of the saturation energy U_{sat} and the gain modulation G_{mod}^{Np} (in nepers). The saturation fluence F_{sat} is the saturation energy per unit area. The other parameters are Planck's constant (h), frequency (ν), and the emission and absorption-cross-section respectively (σ_{ems} , σ_{abs}), all at the operating signal wavelength. The core area A , achievable gain modulation, and saturation fluence set a limit on the extractable energy. It depends on the emission and absorption-cross-sections, which in turn depends on the operating wavelength and doping concentration [5-6, 13, 14]. The cross-sections σ_{ems} and σ_{abs} in the YDF both peak at 976 nm, although a slight asymmetry means that reabsorption shifts the gain peak to 977 nm. The saturation energy of the fiber is calculated to ~ 3.22 mJ at 977 nm and $\sim 4\%$ lower at 976 nm. With a spontaneous-decay lifetime τ of 0.8 ms for Yb:aluminosilicate, the intrinsic saturation power F_{sat} / τ becomes 4.02 W at 977 nm. From this, a small-signal gain slope of 1.08 dB/W with respect to absorbed pump power can be calculated.

The absorption of the YDF was measured with white light which flooded the launch facet, at lengths of 0.12 m, 0.21 m, and 0.27 m. Mode-selective absorption effects are in principle unavoidable when a significant fraction of the light is guided by the core as well as by the cladding, but were not observed in these short lengths. Based on these measurements and on the core / 1st inner cladding area ratio of 0.75, the peak absorption becomes ~ 50 dB/m at 980 nm with small variations between the different measurements, although at least the higher of these values seems reduced by nonuniform absorption effects [17, 18]. Insofar as the 915-nm absorption is accurate, the Yb³⁺-concentration becomes $\sim 1.25 \times 10^{25} \text{ m}^{-3}$. Gain at ~ 976 nm (the zero-phonon wavelength) requires that at least 50% of the Yb-ions are excited. At this minimum excitation, the power lost to spontaneous emission becomes 414 W/m, as recalculated to the pump wavelength. Hence, it is important to not go overlength. The fluorescence power at the excitation level that leads to an excitation level higher than 50% is proportional to the fiber length and becomes much higher for 980-nm amplification than for 1060 nm, where the excitation is much lower. The pump intensity should be at least 0.943 mW/ μm^2 at 915-nm to reach

50% excitation everywhere in the fiber. This translates to 62.3 W of power across the core, which is also the optimal pump leakage. Note that this optimum leakage is reached at the time of the seed-pulse injection. The leakage is lower while the excitation is building up, and thus also the average leakage.

III. ULTRA-LARGE CORE YDFA CONFIGURATION

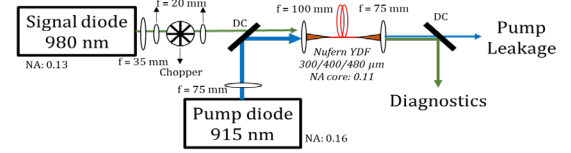


Fig. 1. Experimental layout of the YDFA, co-directionally core-pumping.

The experimental setup as shown in Fig. 1. Our pump source is a 915-nm DL with a 200/220- μm , 0.22 NA pigtail (nLight model e24i). Its maximum output power is 400 W, 95% of which is specified to propagate within an NA of 0.15. The resulting beam parameter product of 150 mrad $\times$ 0.1 mm (pump laser's output end) = 15 mm mrad is well matched to the 110 mrad $\times$ 0.145 mm (effective mode-field radius of the fiber core) = 15.95 mm mrad of the YDF core. If the pump launch efficiency can reach 90% for a launched pump intensity of around 5.45 mW/ μm^2 , then this suggests that a fractional pump leakage of $62.3 / (0.90 \times 400) = 17.3\%$, or -7.62 dB is appropriate. According to Eq. (1), a high gain modulation G_{mod}^{Np} is implicit for amplification of high-energy pulses. Since a pulse can at most extract so much energy that the Yb-gain decreases to 0 Np, it follows that also the initial gain, at the point in time when the seed pulse enters the amplifier, should be high. It also follows that the maximum energy that can be extracted from the gain medium is proportional to the initial logarithmic gain $G_{initial}^{dB}$ [14], where we have switched logarithmic gain unit from Np to dB. The initial gain may be limited by available pump power as well as parasitic emission such as ASE and spurious lasing, which is difficult to avoid at high gain [1, 15]. In our case, however, the power lost to ASE approximately grows exponentially with $G_{initial}^{dB}$, and the spontaneous emission that is captured by the core and thus seeds the ASE grows with the square of NA. In our simulations, a sufficiently low gain in the core (e.g., 20 dB), the reduced overlap of light guided by the second cladding is expected to suppress lasing on cladding-modes. Therefore, a pump leakage of 7.62 dB at 915-nm and a gain of 20 dB at 977-nm, it fixes the average fractional excitation n_2 to 62.10% (in our simulations) when a pulse arrives, and the fiber length to ~ 0.145 -m. We also note that at this excitation level, the logarithmic gain at the secondary peak at 1030-1040 nm is $\sim 60\%$ of that at the primary peak. These gain levels are low enough to suggest that parasitic emission need not be a problem. The experimental setup further comprises a 980-nm DL to seed the amplifier, dichroic mirrors and lenses for coupling signal and pump light into and out of a 1-m YDF (longer fiber led to lower pulse energies in our experimental results), in a co-pumped amplifier configuration, the fiber length was selected after experimental analysis, achieving the highest performance in terms of energy

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extraction. The output end of the YDF was angle-cleaved ($\sim 12^\circ$) to suppress feedback. This angle suffices to largely suppress feedback from the core into the first cladding, too, but signal light reflected at the output facet will be guided by the second cladding, since we did not attempt to strip this light. The seed-DL (IPG PLD-70-974) is pigtailed with a 105/125- μm diameter fiber. It emits a CW beam with an NA of 0.13 and a maximum power of 50 W. This can be on-off-modulated by a mechanical chopper at kHz-level PRF. The pump-DL is driven quasi-CW by a power supply (TDK Lambda GEN50-30). Throughout, this is asynchronously on-off modulated by a waveform generator (Tektronix AFG1022) to produce 130-ms pump pulses at 1 Hz (duty cycle 13%). This mitigates the heat-load that could otherwise damage the YDF in CW operation. The previously calculated average powers do not consider the pump-modulation, and reported experimental data are averaged only for the time during which the pump is on. Thus, the overall experimental average powers are nearly an order-of-magnitude lower than the reported average powers. We used an InGaAs lightwave power meter (8153A mainframe, 81533B interface module and 81525A InGaAs head, Hewlett-Packard) to measure power via an analog signal provided by the power meter. This was fed to an oscilloscope (peak hold mode) and calibrated. This allowed for measurements of the instantaneous optical power with resolution time of 20 ms. For higher-bandwidth measurements, traces were captured with a photodetector connected to the oscilloscope. The traces were calibrated and pulse energies determined through integration.

IV. RESULTS AND DISCUSSION: YDFA CONFIGURATION

We measured 90% pump launch efficiency. The overall pump leakage was measured to be 20% (-7 dB) at 265 W instantaneous launched pump power. Of the leaked pump power, $\sim 70\%$ is found in the core at the output end, while 30% resided in the inner-cladding, as determined by imaging the output with a lens and a silicon camera sensor. The NA of the imaging system exceeded the combined first-cladding and core NA ($= (0.23^2 + 0.11^2)^{0.5} = 0.255$), so imaged light emerging from the core includes the full fraction of light in cladding-guided modes that emerges from the core. Hence, the fraction of the leaked power which is guided by the core is smaller than 70%. The other 30% emerged from the inner cladding. When we take the light distribution at the output end into account, the pump power needed for 50% excitation at the fiber end increases from 62.3 W to 89 W. The amplification performance was evaluated under varying pump powers and seed signal parameters. For the results we report, the pump DL was on-off modulated with 130-ms pump pulses at 1 Hz. First, with 0.9-W CW seeding, the slope of the instantaneous (pump-on) gain was evaluated to 0.136 dB/W with respect to launched pump power. Fig. 2 (a) shows the instantaneous signal gain and output power vs. CW seed power for an instantaneous pump power of 175 W. At the lowest considered seed power of 0.9 W, the

instantaneous gain reaches 7.5 dB. The instantaneous signal output power reaches 47 W for 28 W of seed power, corresponding to 2.2 dB of instantaneous gain. The 19-W increase in signal power represents a pump conversion efficiency of 10.9%.

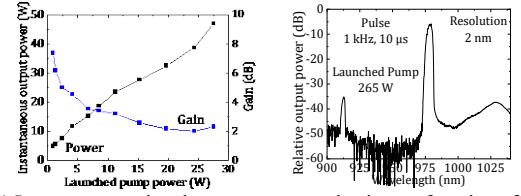


Fig. 2. A) Instantaneous signal output power and gain as a function of launched seed power (CW) for an instantaneous pump power of 175 W. B) Optical spectra of signal output pulses at with 10- μs seed pulses at 1 kHz and instantaneous pump power of 265 W. Peak-to-ASE ratio is ~ 30 dB, FWHM not observed.

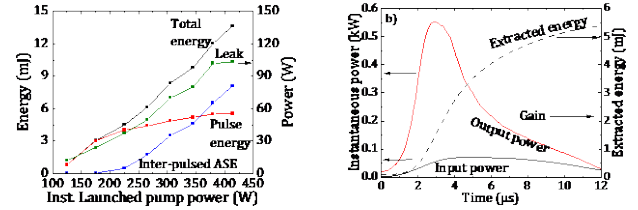


Fig. 3. (a): Output-end energy vs instantaneous launched pump power for seeding with 0.8-mJ, 10- μs pulses at 1 kHz. (b): Time traces of signal power and maximum extracted energy of 4.4-mJ at 1-m amplifier fiber length.

Relevant papers	Core radius (μm)	M^2	Peak Power (KW)	YDF Type	Fiber length (m)	Operating mode
Our Results	150	52.9	0.55	LMA	1	Pulsed
[5] Bouillet et al. (2009)	40	28.3	0.094	PCF	1.23	CW
[6] Armitage et al. (1989)	2.1	0.7	1.00E-05	SM	0.086	CW
[7] Zenteno et al.	3	2.1	6.50E-04	SM	0.5	CW
[8] Bouillet et al. (2010)	35	67.5	63	PCF	1.2	Pulsed
[9] Chen et al. (2021)	52.5	20.2	0.556	LMA	3.4	CW
[10] Lhermite et al. (2010)	10	3.5	20	PCF	3	Pulsed

Table 1. A comparison of our results with the most relevant studies on YDF reported in literature to date, to the best of our knowledge, operating at 97X-nm wavelength. LMA = Large Mode Area, PCF: Rod-type Photonic Crystal Fiber, SM = Single Mode, CW: Continuous wave.

Fig. 2 (b), 3 (a) and (b) show results for seeding with 980-nm, 10- μs , 0.8-mJ pulses at 1 kHz in an on-off modulated system, corresponding to 130 ms when the pump is on. The average seed power becomes 0.8 W and the duty cycle 1%. From the optical spectra shown in Fig. 2 (b) for a pump-on power of 265 W, we can observe that most of the power resides within the signal wavelength 980-nm (OSNR > 30 dB, spectral width of ~ 5 nm, limited by the resolution at 2 nm). Thus, the 1-m YDF was short enough to avoid the strong reabsorption that is common in YDFs at 980-nm [1, 2, 13].

Fig. 3 (a) shows output-end powers and energies vs. instantaneous (pump-on) launched pump power. The average power and energy are related to each other by the 1-kHz PRF. Note also that as always, presented data correspond to the 130 ms during which the pump is on (so the longer-term averaged powers are 13% of the presented powers). Fig. 3 (a) shows that the output pulse energy reaches a maximum of 5.5 mJ of energy for 5.5 dB of energy gain at 414 W of pump power. The total output energy (thus, total average power including inter-pulse

contribution) increases linearly with the launched pump power with a slope of $\sim 44\%$. The inter-pulse energy is noticeable for pump powers of 225 W and above, making up most of the output power at 414 W of pump power. Its slope reaches $\sim 41\%$, thus dominating the 44% total slope. The pump leakage becomes 25% (103 W) at full pump power. However, its slope is higher, 33%, so the leakage gets higher at higher pump powers. This may be due to temperature effects, a Yb-excitation that builds up faster and to higher values (both of which increases the pump leakage), and reduce pump beam quality leading to a larger fraction of pump power in the 1st cladding as the pump power increases. Regardless, it means that the slope of the total output power reaches 67% with respect to absorbed pump power. The counter-propagating output was not measured but also contributes to the total conversion efficiency to 980 nm (even if not useful). The slope efficiency between the total output power and the launched pump power resulted much lower than expected, complications due to the backward emission of the system and the on-off pump modulation of the system. The inter-pulse ASE energies (energy between pulses) start building up and increase rapidly after reaching the threshold of 200-W instantaneous launched pump power.

Fig. 3 (b) shows time traces of the signal power with the same 80-W instantaneous seed signal and launched pump-on power of 414 W. The highest achievable peak power was ~ 0.55 kW for a gain of 8.5 dB, obtaining a maximum extracted energy of 4.4 mJ, for a launched pump-on power of 414 W. Based on the measurements of the instantaneous gain, it is likely that the input pulse should be rising later than presented in the figure. The temporal offset may result from timing of the input pulse or a processing error of the oscilloscope, which could lead to higher gain than calculated.

V. CONCLUSIONS

In comparison to our previous estimations of the initial gain, in Fig. 3 (b) we can observe from the temporal traces that the instantaneous gain drops by ~ 5 dB (or 1.15 Np) after reaching its peak gain (i.e., 9 dB), which implies that the YDFA configuration should have extracted at least ~ 6.5 -mJ. Yet, our XLMA YDFA extracted 72% of the maximum extractable energy (i.e., 4.4-mJ). The shortfall is most likely due to the very strong inter-pulsed ASE (i.e., $\sim 60\%$ inter pulsed ASE) and backward pulse energy emission. Another explanation would be imperfect extinction ratio between the pump power and signal power by the dichroic mirror used, which could imply that a fraction of the extracted energy ($\sim 15\%$) is being neglected, and due to the much higher pump energy in the leakage output, an accurate calculation of the neglected signal energy or the temporal offset of the input pulse may not be entirely possible. Furthermore, the leakage shows that 103-W instantaneous launched pump power (i.e., $\sim 25\%$ of the launched pump power) is not being absorbed by the fiber. Additionally, at instantaneous launched pump power higher than 250-W, the inter-pulsed ASE becomes an issue ($>20\%$). The rapid rise of the ASE and the roll-off of the output pulse energy suggests that we are close to the maximum achievable pulse energy on our

system. Moreover, our core-pumped, YDFA configuration reached up to >8.5 dB energy gain at the peak instantaneous output power at 1-m fiber length, which translates to >8.5 dB/m gain at the 980-nm operating wavelength, higher than other PCF amplifier configurations (e.g., 7.3 dB/m gain) [8], and using a shorter YDF than most LMA system in the pulsed regime [9]. In summary, despite the difficulties of operating at 980-nm signal wavelength [4-10], as seen in Table 1, our results demonstrate the advantages of an XLMA YDFA configuration, achieving over 5.5-mJ of output pulse energy at a 1 kHz PRF with a 10- μ s pulses at 980 nm, using a 1-m fiber, resulting in a simple, efficient mJ-level pulse-pumped laser source at 980 nm with better beam quality compared to most commercial DL and fiber laser systems at 980-nm with similar configurations.

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