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► **To cite this version:**

B. Leconte, Y. Leventoux, Romain Dauliat, Valerian Freysz, S. Vidal, et al.. 1.8 mJ pulses at 1560 nm based on a 55 μm core pure-erbium-doped VLMA fiber. *Optics Letters*, 2024, 49 (21), pp.6293. 10.1364/OL.538256 . hal-04814980

HAL Id: hal-04814980

<https://hal.science/hal-04814980v1>

Submitted on 2 Dec 2024

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1.8 mJ pulses at 1560 nm based on a 55 μ m core pure-Erbium VLMA fiber fabricated using the REPUSIL technology

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XX

Despite the increasing demand of high-energy erbium lasers for LIDAR imaging applications, the scaling of current Yb-Er co-doped technology remains held back by parasitic emission. In this study, we present the first utilization of the REPUSIL[©] powder synthesis method to fabricate a 55 μ m double-clad fiber with a remarkably large modal area. Doped solely with erbium and free of ytterbium, its estimated cladding absorption is of 2 dB/m at 976 nm, enabling short amplification lengths. We demonstrate its potential through direct amplification of a GHz femtosecond laser ($M^2 = 1.12$) and notably, the generation of 1.8 mJ-37ns Q-switched pulses in oscillator configuration ($M^2 = 1.46$).

2024 Optical Society of America

High-power fiber lasers have become the cornerstone of many industrial and research applications due to their simple and compact nature compared to alternative technologies based on massive/bulky amplifiers. Erbium-doped fibers, whose emission is centered around 1.5 μ m, show strong potential for high power and ultra-short pulse generation. These pulses, in femtosecond regime, are particularly useful in applications ranging from multiphoton microscopy to high-order harmonic generation in semiconductors [1–3]. The erbium-based laser emission also stands out by its "eye-safe" nature, making it ideal for on-field applications, such as 3D imaging and telemetry, light detection and ranging (LIDAR), gas measurement (e.g. CO₂), free-space optical communications technologies, or direct energy weapons in defense [4–6].

Yet, the main challenge in enhancing the performance of erbium fiber systems lies in the maximum extractable power, which is directly linked to the fibers geometric and chemical parameters. Increasing the core size reduces the spatial power density, elevating the threshold for nonlinear phenomena and fiber degradation. However, a larger core size can lead to the emergence of higher-order transverse modes, significantly degrading the output beam quality. In addition, the fiber length has to be chosen with care to both favor effective amplification, while avoiding nonlinear phenomena or gain narrowing. Chemically, the solubility of erbium ions into a silica matrix remains limited; at high concentrations, it forms clusters that reduce laser efficiency. In consequence, low rare-earth doping concentrations and low absorption cross-sections limit the maximum achievable gain. As an alternative, ytterbium-erbium co-doping has been widely adopted to increase the absorption cross-section at the cost of unwanted features such as amplified spontaneous emission (ASE) around 1 μ m and challenges in

achieving a low core-cladding index contrast for a large mode area [7–9].

To scale up the average power of erbium amplifiers, several Yb-free very large mode area (VLMA) fibers have been demonstrated. The highest pulse energy, to our knowledge, was achieved by Nicholson et al., with approximately 5 mJ, a pulse duration of 2.6 μ s (FWHM), a repetition rate of 5 kHz, and a M^2 of about 1.5 in a 80 μ m core fiber [10]. Using a resonant pumping scheme at 1480 nm, an absorption of 80 dB/m was achieved. This requires a complex architecture and a non-commercially available high-power WDM. Besides, Khudyakov et al. generated pulses of 2 mJ, 5 μ s, 1 kHz, and a M^2 of 1.43 using a traditional double-clad 976 nm pumping scheme with a tapered fiber whose core size varied from 16.5 μ m to 86 μ m [11]. The adiabatic propagation from the smaller single-mode core to the larger end provides an efficient amplification while maintaining high beam quality. However, these fibers lack versatility due to their fixed lengths, large curvature radius required and manufacturing challenges. State-of-the-art erbium-doped VLMA double-clad fibers, synthesized using the traditional Modified Chemical Vapor Deposition (MCVD) techniques, deliver between 1 and 1.5 mJ with good beam quality [9,12,13]. These performances can still be scaled up by putting effort on the chemistry to enlarge even further the VLMA fiber core. To do so, one must deal with the synthesis of homogenous preform - i.e. free of the central dip or ripples commonly observed on the profile of MCVD-based fibers – whose refractive index can be repetitively controlled between 5.10^{-4} and 1.10^{-3} and enable the emission of a single large mode while the fiber curved.

To meet these specifications, an alternative method for manufacturing erbium-based fibers has been employed here. In fact, both active and passive materials were synthesized using the

REPUSIL[©] powder sintering and vitrification technology, previously approved for the realization of high power Yb-fiber laser [14]. We introduce the first application of our powder synthesis method for the fabrication of a VLMA double-clad fiber, featuring a 55 μm core composed of an Er-doped aluminosilicate host matrix free of ytterbium co-doping. When pumped at 976 nm, this fiber exhibits a cladding absorption of 2 dB/m and a slope efficiency in a continuous wave (CW) oscillator scheme of 30% versus launched pump power and 40 % vs absorbed pump power. One advantage of this VLMA fiber is its ability to amplify over short lengths (< 5 m) with a large effective area, which enables high gain without significant parasitic amplified spontaneous emission (ASE). We demonstrated the possibility of achieving a gain greater than 25 dB (at 10 W average power) in a direct amplification configuration of GHz femtosecond pulses ($M^2 = 1.12$), without significant nonlinear effects nor ASE. This ultrashort pulses regime is oftentimes addressed for applications such as very high-rate ablation without thermal effects on materials like metals or silicon [15]. Additionally, we have shown its potential by reaching up to 1.8 mJ of energy per 37 ns pulse in a free-space Q-switched cavity based on this fiber ($M^2 = 1.46$). To our knowledge, this energy level is the highest obtained using a traditional single-mode double-clad Er-doped fiber. This work paves the way to a new generation of high-power erbium-doped fibers for applications such as LIDAR systems, remote sensing, optical communications, and industrial applications requiring energetic laser sources.

Fiber fabrication and CW characterization: Both active and passive materials were synthesized using the REPUSIL[©] powder sintering and vitrification technology, which allows for precise control of refractive indices in both absolute value and homogeneity, and additionally offers a production capacity about 50 times larger than that of the MCVD process [16]. The REPUSIL process involves doping and purification of powders using a suspension-doping step. This enables the synthesis of uniformly doped silica in fairly high amount (ca. 200g), starting with high-purity gas phase-formed silica nanoparticles and water-soluble compounds of the doping elements. The doping ions precipitate as pure or mixed hydroxides on the surface of the suspended silica particles. After dehydration, green bodies are formed, purified and at last vitrified at high temperatures to produce transparent glass samples.

As shown in figure 1.a, the VLMA fiber was fabricated by "stack and draw". The 55 μm core, doped with Er_2O_3 and Al_2O_3 ions (0.07 mol% and 2.8 mol% respectively), is surrounded by a passive Al_2O_3 -doped silica pedestal whose composition was set to provide a relative refractive index difference of $8 \cdot 10^{-4}$ (NA of 0.048). A home-made hexagonal-shaped pure silica tube was used to jacket the final stack and delimits the fiber outer cladding. Its shape favors effective pump absorption by promoting the homogeneity of the transverse distribution of the pumping power within the cladding. Once drawn, the fiber outer cladding is of 270x310 μm . A low-index polymer, crucial to maintain mechanical strength and protect the fiber against humidity and impacts, was deposited on the fiber surface, contributing in enhancing the cladding numerical aperture (NA) and decreasing optical loss, ensuring efficient pump power guidance throughout the fiber's length. The overall absorption at 976 nm of the pump

power within the cladding is estimated at 2 dB/m in a saturated gain regime.

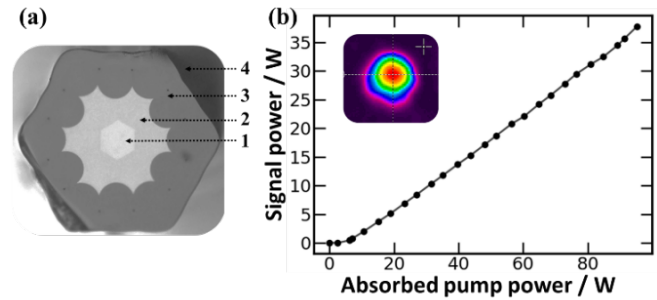


Fig. 1 a) Image of the cross-section of the fabricated Er-doped VLMA fiber. 1: 55 μm Erbium-doped core, 2: Pedestal made of Al-doped cladding material (120x155 μm), 3: Pure silica glass (270x310 μm), 4: Low-index acrylate coating (600 μm); b) Output power at 1560 nm as a function of the absorbed pump power of the CW laser and near-field intensity distribution in inset.

To evaluate the performance of the fiber, a 6m-long piece of fiber was first used in a simple oscillator architecture composed of a highly reflective mirror serving as end mirror of the cavity. The output mirror was formed by the cleaved end-facet at 0° of the fiber. The fiber pumping is achieved in free space by a multimode laser diode delivering up to 140 W at 976 nm (100 μm fiber NA 0.22). At full pumping power, up to 40 W of average power at 1560 nm were delivered by a diffraction-limited beam, whose mode field diameter (MFD) was estimated to be higher than 45 μm . Unlike high power Er-Yb co-doped fiber lasers, the efficiency slope shows here linear fashion, and that even at maximum pump power ($\eta = 43\%$ plotted versus the absorbed pump power - see Figure 1.b). This also confirms the absence of performance degradation due to thermal effects. The overall opto-optical efficiency is 30%.

Direct amplification of fs pulses: High-power femtosecond pulses are traditionally obtained using the Chirped Pulse Amplification (CPA) method, which circumvents the appearance of deleterious nonlinear effects. This method involves a rather complex architecture for pulse dispersion and recompression. Consequently, recent studies are focused on the direct amplification of femtosecond pulses using VLMA fibers without dispersive stages. As a cornerstone, the generation of sub-MW pulses in a tapered Erbium-doped fiber has been first proved [17]. In the current work, the efforts are further brought on demonstrating that VLMA fiber can provide high amplification gains without the appearance of ASE in low-power pulses, thus eliminating the need for a pre-amplification stage. To do so, a simple MOPA setup (Master Oscillator Power Amplifier) was build out from a 30-mW femtosecond seeding source (Menhir Photonics) whose 500-fs "GHz" pulses feature a spectral bandwidth of 14 nm. It is worth noting that these pulses were not intended to be diffraction limited. A free-space isolator was introduced straight after the seeder to ensure protection against laser reflection. The pulses were then directly amplified (no pre-amplifier) into a 4.5 m long 55 μm core Er-doped VLMA fiber, whose end facets are angled-cleaved to prevent parasitic laser effects. Due to the large core size and low NA, a special attention was given to the mode matching at the fiber input. The fiber is pumped at 976 nm in the counter-propagative direction keeping the above-mentioned multimode pumping laser diode.

Preliminary results show the amplification of pulses at 1560 nm with an opto-optical efficiency of 25% up to 10 W of average power, corresponding to an energy of 10 nJ per pulse for a pump power of 45 W injected into the cladding. It is worth noting that despite the high amplifier gain (> 25 dB), no parasitic laser effects nor ASE were observed.

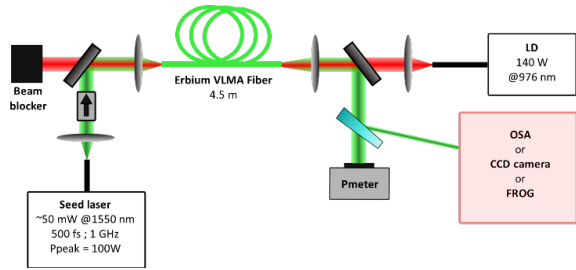


Fig. 2: Experimental setup for GHz femtosecond direct amplification

Through the amplification mechanism, the pulses spectrum underwent a narrowing from 14 to 8 nm. In addition, the temporal traces, displayed in Fig.3, were acquired using a commercial Frequency-Resolved Optical Gating (FROG) device, providing pulses duration of 1.1 ps, which is in good agreement with the expected linear elongation due to the chromatic dispersion of the fiber (anomalous dispersion regime at 1560 nm).

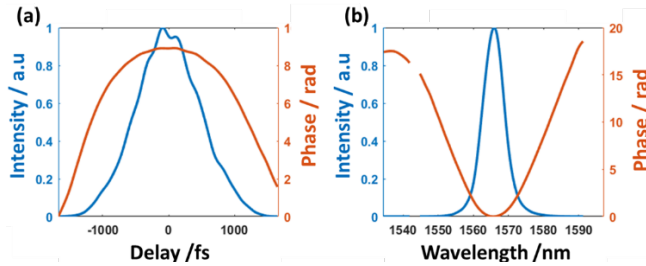


Fig. 3 FROG trace of the amplified fs pulses, (a) Reconstructed temporal trace and (b) Reconstructed spectral trace

High energy nanosecond oscillator: As previously stated the energy scaling in Er-doped fiber lasers is of high interest. To demonstrate the potential of our fiber in this field, we used it as the gain medium in a Q-switch cavity. This architecture can generate extremely energetic pulses lasting several tens of nanoseconds. The experimental setup, shown in Figure 4, comprises a 4.5-meter-long segment of the 55 μm core VLMA. On the pumping side, the fiber end facet is perpendicularly cleaved and acts as the first mirror in the cavity thanks to the 4% Fresnel reflection. The opposite facet is angle cleaved to prevent spurious reflections. The fiber is pumped using the same 976 nm diode as before, the pump light being launched into the fiber after passing through a 1030 nm reflective dichroic mirror tilted at 45°. The output beam is then focused into an acousto-optic modulator (AOM) controlled/triggered by an arbitrary function generator, allowing for optical gating at frequencies ranging from a few Hz to several hundreds of kHz. The gate opening duration is adjustable and can be reduced to 90 ns. The first-order beam from the AOM is directed onto a metallic mirror closing the cavity. At the laser output, the pulses are measured using a power meter. A portion of the signal is sampled by a silica wedge plate, enabling

the acquisition of the temporal and spectral traces, as well as the spatial profile of the beam.

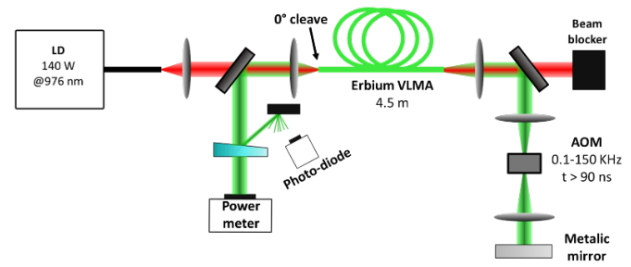


Fig. 4: Experimental Q-switch setup generating ns pulses

Figure 5.a. shows the typical spectrum of this oscillator, centered at 1560 nm and consisting of a set of fine spectral lines over the broadband of gain, characteristic of the Q-switch architecture as no spectral filter was applied in the cavity. For LIDAR applications, it would be interesting in future work to use a MOPA configuration in which the VLMA fiber would simply amplify the nanosecond signal from a single-frequency pulsed cavity. Figure 5.b. displays the typical temporal trace of our Q-switch pulses, yielding pulses of 37 ns (FWHM).

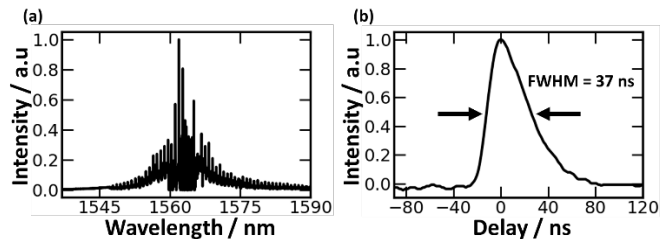


Fig. 5: Typical (a) spectrum and (b) temporal trace of the Q-switch architecture.

To maximize the energy extracted from the oscillator, we employed a modulation frequency as low as 1 kHz. It is worth noting that at these frequencies, the millisecond time interval between pulses exceeds the fluorescence lifetime of erbium. A significant portion of the measured power consists of intra and extra-pulse amplified spontaneous emission (ASE), complicating the accurate measurement of pulse energy. These issues have been discussed previously, and a simple pyroelectric energy meter cannot be used due to the variable nature of ASE over a pulse period. In this study, we adopted a similar solution than Kotov *et al.*, which involves using an integrator-type electronic circuit [9]. Our system is depicted in Figure 6.a. where the photodiode converts incident light into a current proportional to the light intensity. The capacitor C accumulates charge proportional to this current. Consequently, the output voltage of the operational amplifier increases over time. This increasing voltage permits the measurement of the cumulative time-dependent light intensity while highlighting signal and ASE. Figure 6.b. illustrates a typical curve obtained with this setup, showing the variations in light intensity between two laser pulses. The abrupt jumps correspond to the detected pulses, while the linear rises between the jumps represent the continuous integration of the ASE. This curve was generated with a pump power of 23.4 W, which corresponds to our maximum measured signal power of 2.7 W. It can be seen that only 68% of the overall

power lies under the pulses envelop. This allows us to estimate the maximum energy at 1.84 mJ, which correspond to 50 kW of peak power. No nonlinear distortions were observed, nor in temporal, neither in spectral way, showing the main advantage of this VLMA structure. The stability of a Q-switched cavity is a delicate balance between gain and loss. In our setup, this stability range allowed us to achieve stable pulses ranging from 0.7 mJ to 1.84 mJ as depicted in Fig. 6c. Therefore, the maximum energy value is not intrinsic to the damage threshold of our VLMA. The previously mentioned MOPA configuration would allow us to determine the true energy limit of our fiber.

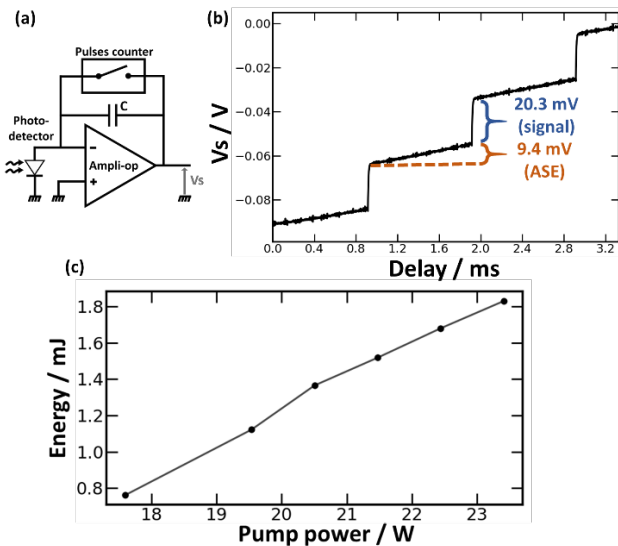


Fig. 6: (a) Electronic integrator schematic; (b) typical curve obtain with the integrator setup; (c) variation of the oscillator output energy as a function of pump power

One of the main advantages of fiber lasers is their exceptional beam quality, which allows for unparalleled laser brightness. To quantify this quality, we utilized an M^2 measurement system. The results, depicted in Figure 7, show an M^2 value of 1.12 in the MOPA configuration, which prove the transverse singlemode propagation along fiber. The beam quality at the output of the Q-switch setup was measured at 1.46, which is still quite good. We believe that the loss of quality is due to the AOM in the cavity, which degrades the beam and consequently impacts the M^2 measurement.

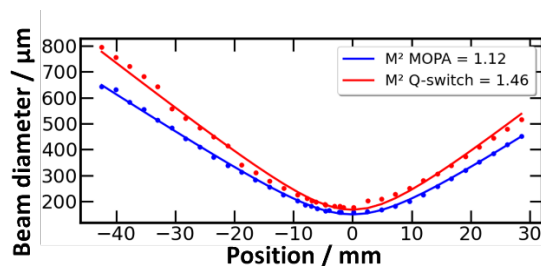


Fig. 7: Beam diameter as a function of displacement during the M^2 measurement for the MOPA configuration (blue) and the Q-switch oscillator configuration (red).

Conclusion: In this study, we have successfully demonstrated the fabrication and utilization of a 55 μm pure-erbium VLMA fiber using the innovative REPUSIL[®] powder synthesis method. This approach offers significant advantages over traditional MCVD techniques, including higher production capacity and precise control over refractive indices, enabling the fabrication of fibers with large mode areas. Our experimental results highlight the capability of this new fiber to generate high-energy pulses, achieving a state-of-the-art 1.8 mJ in a Q-switched oscillator configuration ($M^2 < 1.46$). This performance underscores the potential of erbium-doped fibers in producing high-power, ultra-short pulses, which are crucial for applications such as LIDAR, remote sensing, and industrial laser systems. The VLMA fiber's ability to maintain high beam quality ($M^2 < 1.12$) and efficient amplification over short lengths without significant nonlinear effects or ASE marks a substantial advancement in fiber laser technology. These characteristics not only enhance the practicality of erbium-based fiber lasers for demanding applications but also pave the way for further developments in high-power, eye-safe laser systems. Future work will focus on optimizing the fiber design and exploring its integration into more complex all fiber laser architectures, such as MOPA configurations, to fully exploit its capabilities, reduce the laser spectral linewidth and determine the ultimate energy limits.

Funding. The authors thank the funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 863307 for the fabrication of the erbium-doped fiber.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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