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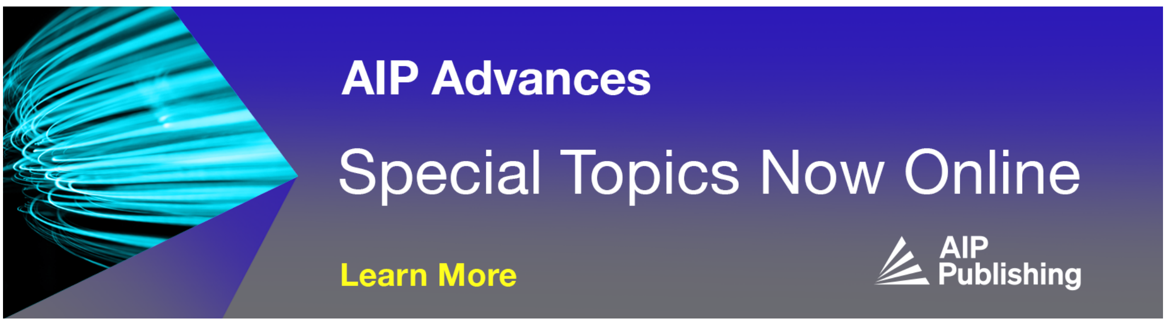

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ABSTRACT

This study examines the influence of quenching dynamics on the efficiency of erbium-doped fiber amplifiers (EDFAs) with high erbium-ion (E^{3+}-ions) doping concentrations, comparing pulsed and continuous wave core-pumping methods. Our findings indicate that quenching, driven by energy transfer upconversion, substantially impacts signal gain in these fibers. The core-pumping configuration demonstrated significantly higher gain per unit length than both low-doping EDFAs and cladding-pumping systems, with effective energy storage achievable through short pump pulses to reduce concentration quenching effects. The highly doped homemade fiber (fiber under test - FUT No. 3) achieved a gain per unit length exceeding 8.4 dB/m, outperforming the lower doped commercial fiber (FUT No. 4) by a factor of 6.4, although FUT No. 4 displayed better compatibility with the core-pumping system. Additionally, the highest gain per unit length for a counter-directional, cladding-pumped amplifier configuration with a high-concentration fiber was recorded at 5.9 dB/m at a 1560 nm signal wavelength with a 2 μs pulse duration, positioning FUT No. 3 as a highly efficient option for high-gain applications despite its high doping concentration. Our experimental analysis of quenching dynamics not only highlights an approach for scaling pulse energy using shorter fiber lengths to mitigate nonlinear effects but also provides valuable insights into quenching-influenced gain behavior in pulsed fiber amplifier systems.

INTRODUCTION

The development of fiber lasers began in 1961 with Snitzer's groundbreaking work on laser oscillation in glass and the potential for fiber-based operation.[1] Over the decades, fiber lasers have gained prominence due to their numerous advantages, including established fabrication techniques, low optical losses, and efficient pumping with compact diode lasers. The fiber itself serves as both the waveguide and gain medium, offering a broad gain bandwidth and reducing the reliance on bulk optics and intricate mechanical alignment.

Fiber lasers are typically pumped optically through either core-pumping or cladding-pumping methods, making the properties of the pump sources crucial for achieving high power.[2] Both continuous wave (CW) and pulsed fiber laser systems constantly require technological advances due to the need for technological advances in power and efficiency. Rare-earth-doped fibers, particularly erbium-doped fibers (EDFs), have been central to these advancements, enabling the development of high-power fiber amplifiers for a variety of applications.[3]

Erbium-doped fiber amplifiers (EDFAs) are versatile and compact optical sources with significant roles in telecommunications and sensing technologies.[3,4] Among their many applications, EDFAs are integral to Light Detection and Ranging (LIDAR) systems, which rely on pulsed lasers for remote sensing, imaging, and environmental monitoring. The 1.5–1.6 μm emission wavelength range of erbium-doped fibers is particularly advantageous for LIDAR due to its excellent atmospheric transmission and "eye-safety" characteristics.[5] In addition, pulsed lasers play critical roles in diverse fields, including atmospheric monitoring, autonomous vehicle navigation, geological surveying, and medical diagnostics.[6–9] Their ability to generate high peak powers in short pulses makes them invaluable for precision applications in material processing, micromachining, and nonlinear optical studies.[10–12]

However, the quest for higher output powers and pulse energies in EDFAs presents challenges, particularly with nonlinear effects like four-wave mixing (FWM) along with amplified spontaneous emission (ASE). Though some nonlinear effects like Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) can have beneficial applications,[13,14] they pose significant challenges in pulsed lasers as energy levels increase. These issues are exacerbated in longer fibers and require innovative approaches, such as using shorter, highly doped fibers, to manage these effects. One significant concern in highly doped erbium fibers is quenching, which reduces amplifier efficiency by affecting energy transfer and storage within the fiber.[15,16]

Addressing quenching dynamics is crucial for optimizing high-energy pulse generation via techniques that mitigate detrimental nonlinear effects. Research has shown that short pump pulses can extract high energy from partly quenched, highly doped EDFAs, though at the cost of lower pump conversion efficiency.[17] This strategy enables high small-signal gains and pulse energies exceeding several times the saturation energy, even with short fiber lengths (e.g., <2.6 m). Such configurations have demonstrated superior energy extraction per unit core area and length compared to unquenched EDFs.[17]

Our work builds on these findings, proposing an all-fiber, compact core-pumped EDFA system using a short erbium-doped fiber. This approach minimizes nonlinear effects by reducing the pump overlap and fiber length while maintaining high doping concentrations. Core-pumping configurations offer several advantages, including low cost, simpler design, and reduced energy consumption, making them attractive alternatives to conventional cladding-pumped EDFAs.[11] By leveraging the shortened lifetime of quenched fibers, we aim to extract more gain per unit length despite the presence of quenching dynamics. This study explores the potential of achieving high energy extraction in a highly doped erbium fiber amplifier, with the goal of improving performance and mitigating nonlinear effects, ultimately contributing to advancements in pulsed laser applications.[12]

Quenching dynamics

Many factors can limit the performance of an amplifier, including the pumping configuration and fiber doping concentration, such as quenching. For high-energy pulses, the most fundamental limitation is parasitic emission at high stored energy and gain, including unavoidable amplified spontaneous emission (ASE). Equations (1) and (2) estimate the available stored and extractable energy from a fiber amplifier,

$$\boldsymbol{E_{extr}} = \boldsymbol{U_{sat}} * \boldsymbol{G_{mod}^{Np}}, \tag{1}$$

$$\boldsymbol{U_{sat}} = \boldsymbol{A} * \boldsymbol{F_{sat}} = \boldsymbol{A}\left(\frac{\boldsymbol{h\nu}}{(\boldsymbol{\sigma_{ems}} + \boldsymbol{\sigma_{abs}})}\right). \tag{2}$$

The extractable energy (E_{extr}) is determined by the product of the saturation energy (U_{sat}) and the gain modulation in Nepers (G_{mod}^{Np}). The saturation fluence (F_{sat}) is the saturation energy per unit area. The other values are Planck's constant (h), frequency (ν), and the emission and absorption-cross-section, respectively (σ_{ems}, σ_{abs}). The saturation fluence and core area (A) set a limit on the stored energy and, consequently, the extractable energy. It depends on the emission and absorption-cross-sections, which in turn depend on the operating wavelength and doping concentration.[16,18] The cross-section spectra from the homemade FUTs (i.e., Er^{3+}-aluminosilicate) used for the analysis in this article are shown in Fig. 1.

As of the time of writing, the generally held view of the standard doping concentration in Er^{3+}: aluminosilicate fibers is ~1000 ppm erbium concentration. A high-concentration EDF can increase the pump absorption and gain in a fiber of a specific short length, as well as the energy stored in the excited erbium population. However, at high concentrations (i.e., much higher than 1000 ppm), Er^{3+}-ions experience detrimental quenching effects due to interactions between neighboring erbium ions.[17,19–21] Although tailored host glass compositions, e.g., co-doped with Al_2O_3, P_2O_5,[18,22,23] as

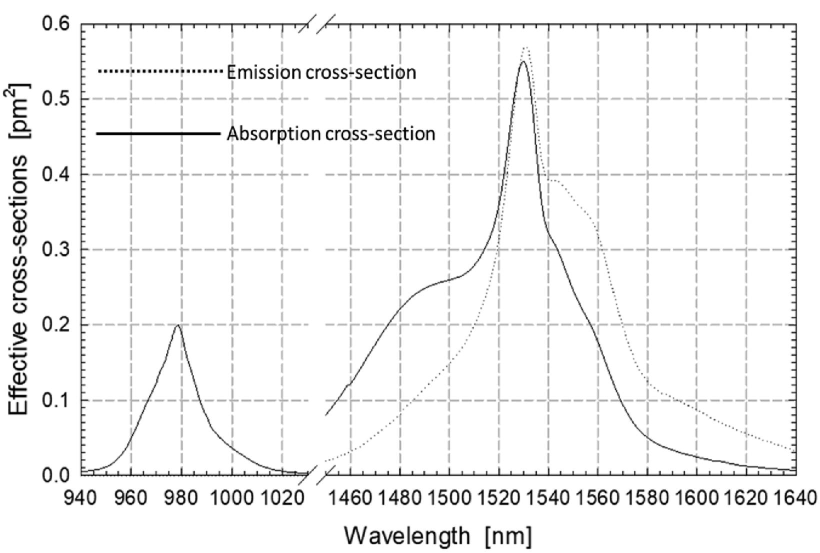

FIG. 1. Plot of cross-sections vs wavelength for the homemade FUTs (Er^{3+}: aluminosilicate) [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

well as nanoparticle doping,[24,25] can mitigate this effect, the quenching still reappears gradually at higher concentrations. Despite extensive research on quenching effects in erbium-doped fiber (EDF) systems, many details remain unclear.[16–20,26] This study does not seek to fully elucidate these details but instead focuses on experimentally demonstrating and discussing the detrimental impact of quenching dynamics on EDF system performance.

In practice, quenching is often modeled as an unsaturable absorption, often tied to a cluster (e.g., pair) model. A scheme following this model is presented in Fig. 2. As a result of quenching and unsaturable absorption, a signal photon emitted inside the fiber may be lost instead of contributing to the signal output, and an absorbed pump photon may fail to excite an erbium ion. Instead, the interaction between nearby excited Er^{3+}-ions, especially in the case of clustered ions, leads to energy-transfer up-conversion (ETU), a phenomenon in which rare-earth ions exchange excitation energy among each other. Insofar as this is more likely to happen at high concentrations when the Er^{3+}-ions are closer to each other on average and more likely to cluster, this is also called concentration quenching. If the upper laser level for some laser transition is quenched, the upper-state lifetime is reduced, raising the threshold pump power of the EDF laser and reducing the gain of the fiber amplifier.[20] Although the lifetime shortening can be gradual and continuous and then modeled as a lifetime shortening that can be modest, for clustered ions, the ETU process is often assumed to be instantaneous. The lifetime is then zero, and the quenching is then modeled as unsaturable absorption.

Nevertheless, it should be noted that ETU is a highly complex process, and the description provided here is simplified. Additionally, Er^{+3}-ions are only partially quenched in three respects, with some Er^{+3}-ions assumed to remain completely unaffected by the quenching.

In the pair model we assume (Fig. 2), it is easy to excite one ion in each pair. Additionally, 50% excitation results in gain for wavelengths longer than the zero-phonon wavelength of Er^{3+} at 1.53 μm. Both ions in a pair can be excited for a brief period. Notably, the unsaturable absorption model may be overly simplistic for certain regimes. The impact of unsaturable absorption and ETU depends on the amplifier configuration and operating regime.[20,27–29]

In addition to the unsaturable absorption and ETU in clusters, leading to very short lifetimes, there is homogeneous ETU that leads to much more modest but still distinct reductions in fluorescence lifetime of the upper-state lifetime ($^4I_{13/2}$). This is normally of the order of 10 ms. If this is reduced, it causes a proportional raise of the threshold pump power of a laser and a reduction of small-signal gain efficiency of a signal amplifier. For example, a lifetime reduction by 50% doubles the laser threshold. However, the effect on slope and power conversion efficiency, as well as energy storage, is more modest and can be negligible even when the lifetime shortening is significant.

Commonly, the fiber amplification of signal pulses employs CW-pumping due to its simplicity. In CW-pumping of pulsed lasers, the population inversion decreases during the signal pulses as this extracts energy stored in the erbium ions. Then the population inversion replenishes between the pulses, allowing the same amount of energy to be extracted once again by the next pulse. CW-pumping benefits from long lifetimes, since then the absorbed pump power can be integrated over a longer time into large amounts of stored energy.

Moreover, Fig. 3 shows the conceptual behavior of the excitation level in a given fiber under test (FUT) using pulse pumping configuration. As illustrated, the short lifetime makes CW pumping less appropriate. For a pulse-pumping, the pump pulses initially excite the ions to higher energy levels (i.e., increase the excitation level in the fiber) and continue increasing until the pump pulse stops. The ions remained excited after the pump pulse. Next, the coming seed signal pulse extracts the energy from the excited ions (i.e., decreases the excitation level in the fiber), increasing the output signal energy. Ideally, the whole storage and extraction cycle is of the order of the lifetime or shorter, to allow for efficient operation also with short lifetimes.[19]

Therefore, pulse-pumping, unlike CW-pumping, can save energy within the FUT, assuming the pulse period exceeds the effective lifetime of the gain medium shortened by the quenching dynamics as well as ASE.

This approach, alongside the all-fiber, core-pumping, and short fiber configuration, can ensure that we can mitigate the detrimental effects of not only the quenching dynamics but also nonlinear effects, allowing for a more efficient EDFA system. However, it is important to clarify that there is no possible way (as of yet) to nullify

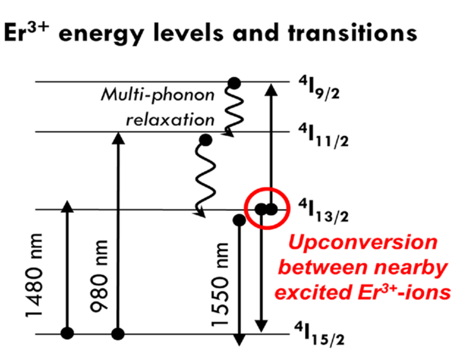

FIG. 2. Simplified concentration quenching model in a EDF system, illustrating the behavior of the partly or fully quenched Er^{3+} ions [Reprinted with permission from Rojas *et al.*, "Efficient extraction of high pulse energy from partly quenched highly Er^{3+}-doped fiber amplifiers," Opt. Express **28**, 17124–17142 (2020). Copyright 2020 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

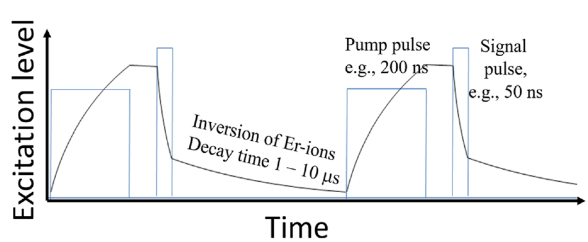

FIG. 3. Conceptual behavior of the excitation level for pulse-pumping [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

these detrimental phenomena; this design aims to mitigate or avoid them in order to increase the gain efficiency.

One can also consider temporally overlapping signal and pump pulses, which, when possible, can be advantageous. However, we consider the case where the signal pulse is short compared to the pump pulse. Then, even if the signal overlaps with the tail end of the pump pulse, the pump energy deposited in the overlapping part can be neglected, so that practically all energy is deposited before the signal pulse arrives.

The overlap factor (Γ) between the pump and the core further modifies the absorption of the signal fiber amplifier. In the case of core pumping, the overlap factor is usually ignored since it is typically close to unity. Note also that the operating pump absorption (when the laser ions are partly excited) can differ substantially from the small-signal absorption, and the change in operating absorption can be quite different from what the overlap suggests.[29]

The absorption of the pump pulse energy by the FUT is an indispensable factor to achieve sufficient fiber laser performance. In order to extract the maximum energy at a given wavelength, it is desirable that the signal gain should be as high as possible while ensuring sufficient absorption of the pump energy pulses, described by equation Eq. (3), where T is the transmittance and A_{Np} is the absorption in nepers (NP),

$$T = 1/e^{A_{Np}}. \tag{3}$$

The pulse energy extractable from a fiber amplifier is strongly limited by unwanted amplified spontaneous emission (ASE).[30] Furthermore, when the pulse energy reaches saturation, the output pulse will be distorted. This is a result of the direct connection between stored energy and gain. Therefore, the leading edge (A1) of the pulse will see a high gain due to the initially high stored energy. The concomitant high energy extracted by the pulse depletes the population inversion, so the rest of the pulse, at the trailing edge (A2), will decrease in a quasi-exponential fashion.[31] With rectangular input pulses, the gain modulation is described by the following equation:

$$G_{mod}^{Np} = Ln(A1/A2). \tag{4}$$

The absorption as well as the gain of erbium-doped fiber amplifiers (EDFAs) can be written in terms of the overlap and other parameters of the amplifier as follows [Eq. (5)]:

$$G_{dB}(\lambda) = 4.343\Gamma L N_0[(\sigma_{ems}(\lambda) + \sigma_{abs}(\lambda))n_2 - \sigma_{abs}(\lambda)], \tag{5}$$

where the gain (G_{dB}) is determined by the overlap of the launched beam with the rare-earth doped core area (Γ), the fiber length (L), the rare-earth doping concentration (N_0), and the emission-cross-section and absorption-cross-section (σ_{ems}, σ_{abs}), which is given by the factor in the square brackets.[5,20]

Both the pump and signal pulses will be affected by distortion as well as the limited pulse energy. However, assuming that the core composition and area of the pump fiber and the signal fiber amplifier are equal, the saturation energy calculated in the signal wavelength will always be higher than at the pump wavelength. The reason is that the saturation energy decreases monotonically from longer to shorter wavelengths until the cross-section peaks at 1.53 μm. Operation at shorter wavelengths than 1.53 μm is not realistic, since the gain quickly becomes smaller and the ASE at the gain peak becomes severe. Therefore, the limited pump energy sets an upper limit on the signal energy that can be extracted from the FUT.

EXPERIMENTAL RESULTS AND DISCUSSION

Core pumping with CW and pulsed Er-doped fiber source: Experimental layout

The quenching processes such as ETU often create additional fluorescence at other wavelengths.[23,27–29] This can be used to detect and analyze quenching. To achieve this, we use the setup described in Fig. 4(a). Evidence of the ETU process in highly EDF is shown in Fig. 4(b). These will be explained in the following, with reference to two Er^{3+}-doped FUTs.

FUT No. 1 (NRL-160415) had a 0.13-NA, 20-μm-diameter Er^{3+}-doped aluminosilicate core centered in a 125-μm diameter circular inner cladding, coated by a low-index polymer. The core absorption measured to be up to 95 dB/m at the 1530-nm peak.

FUT No. 2 (NRL-170525) had a 0.18-NA, 45-μm-diameter Er^{3+}-doped aluminosilicate core centered in a 264-μm diameter octagonal-shaped inner cladding, coated by a low-index polymer. The core absorption reached up to 36 dB/m at the 1530-nm peak. In this measurement, the fiber length is 0.2 m for the FUT No. 1 and 0.5 m for the FUT No. 2, conserving the same Er-concentration x fiber length product for both FUTs.

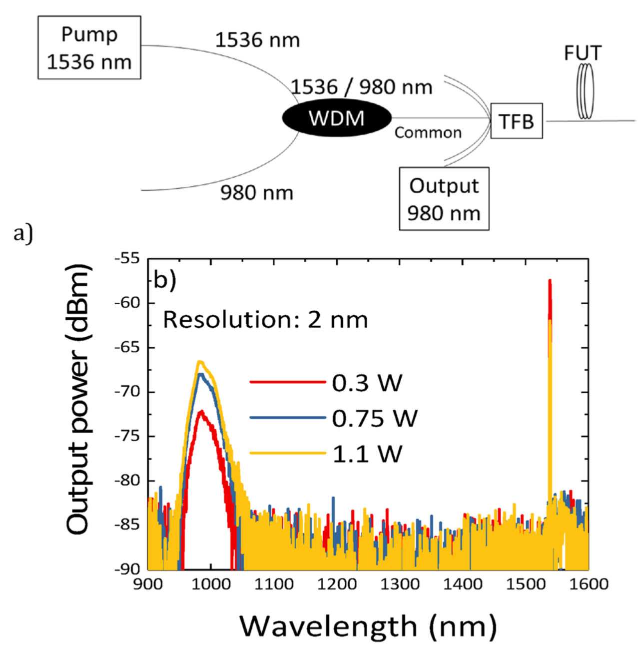

FIG. 4. (a) Upconversion lifetime setup used to detect and study the presence of ETU. FUT No. 1 and No. 2 were used in this setup. (b) Optical spectrum for different values of CW-pump at 1536 nm for FUT No. 1 and No. 2, but only FUT No. 1 showed fluorescence at ~980 nm [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

In the setup described in Fig. 4(a), the Er^{3+}-ions are excited at 1536-nm with a high-power CW-pump source (reaching up to 1.1 W). The CW-pump source is spliced to a wavelength-division multiplexer (WDM) and then to the signal port of a tapered fused-bundle (TFB), the common port of which is finally spliced to FUT No. 1. 1536 nm CW-pump light was launched into the FUT through the WDM and TFB. Then, the pump ports (which are normally used to launch additional pump light into the fiber) are used to collect fluorescence at 980 nm. Since the FUT No. 1 is a double-clad fiber, only a small part of the fluorescence light is captured by the core, while most of it is captured by the inner-cladding. The TFB allows the collection of the fluorescence light propagating in the inner-cladding.[19]

If instead the FUT was a single-cladding optical fiber, then the fluorescence light would be propagating in the core, rather than in the inner-cladding. Because of the strong absorption at the 980 nm wavelength in the EDF, this would have resulted in reabsorption of the 980-nm fluorescence light, making it difficult to detect. Therefore, it is better to have the 980-nm fluorescence light propagating in the inner-cladding, where there is no absorption, instead of propagating in the core. Nevertheless, the setup still allows for 980-nm light propagating in the core of the FUT to be measured from the WDM. The fluorescence light at the 980 nm wavelength shown in Fig. 4(b) is attributed to the ETU process expected from a highly doped EDF, reaching saturation at ~1 W CW-pump power.

To assess the dynamics of concentration quenching, we targeted the modest lifetime shortening of the fluorescence lifetime shown in Fig. 4(b) in FUT No. 1 at 980-nm. This is much easier to measure than the short lifetime of clustered ions. The measurement used pulsed excitation with the 980-nm diode laser, which does not allow reaching high excitation levels. Longer pulses with the same peak power (or even CW-pumping) allow for higher excitation levels but have the disadvantage of selectively exciting unquenched ions (with long lifetimes). Although lifetime shortening could be seen in FUT No. 1, it was relatively modest. Therefore, it was deemed unfruitful to analyze the results in detail (given also the resulting limited impact). A correlation between the lifetime shortening effects of concentration quenching and the gain efficiency of the FUT in a laser amplifier configuration does exist in Refs. 1 and 2. Rather than focusing on the dynamic effects of concentration quenching by examining lifetime shortening in FUT No. 1, this article emphasizes the more critical impact of quenching dynamics on the measured gain performance in the core-pumped amplifier configuration.

Core-pumping of EDFAs has the advantage of being able to use shorter fibers, leading to lower optical nonlinearities.[11,12] Specifically, we investigate pulsed EDFAs in-band pulse-pumped by another Er-doped fiber source, which is deemed to be the most realistic choice of pump source. We also mention that pulsed 0.98-μm core-pumping is unrealistic because of the lack of practical pump sources with sufficient energy fluence.

The experimental layout for this in-band-pumping work is shown in Fig. 5. It comprises tunable-wavelength pulsed seed and pump sources and a FUT.

The pulsed pump source is composed of the ring laser (seed), an acoustic-optic modulator (AOM), and an EDFA (~1 W). The ring laser is composed of two polarization-combined pump diode lasers at 1470 nm, a wavelength division multiplexer (WDM) from Gooch & Housego (G&H), a coupler (70/30), an isolator to control the direction of the ring laser output, an EDF as a gain medium, and the tunable filter (TF), which determines the output wavelength. For the signal "seed" pulsed laser, the setup consists of a tunable laser diode source as the seed, the device modulating the seed laser (i.e., AOM), and an isolator to protect the equipment from leaked pump pulse energy of the signal fiber amplifier. Additionally, the WDMs are used for combining and separating pump- and signal light.[19]

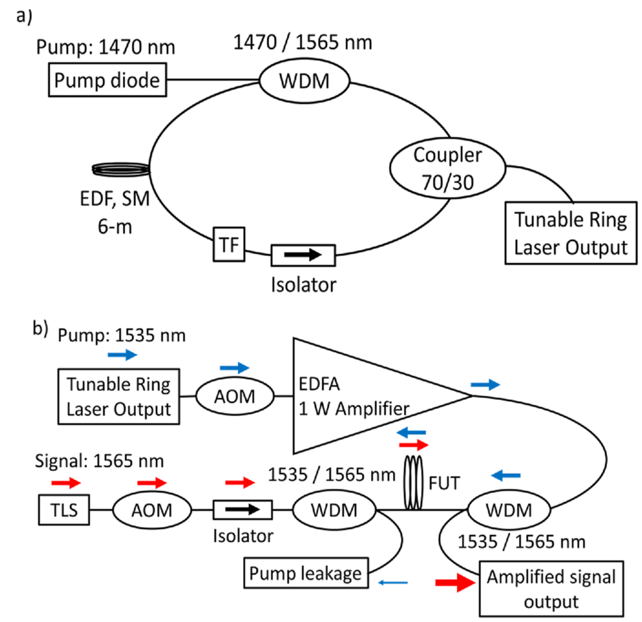

FIG. 5. Setup for pulsed core pumping. (a) Ring laser (CW) incorporating a tunable filter (TF) that forms part of the pump pulse generator. (b) Top part of the pump pulse generator; composed of the ring laser (seed), the AOM, and an EDFA (~1 W). The bottom part is the signal amplifier setup, composed of a tunable laser source (TLS), an AOM, an isolator (ISO), two WDMs, and the signal fiber amplifier. The blue arrows show the direction of the pump pulses, and the red arrows show the direction of the signal pulses [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

A laser diode controller drives the diode lasers. Their outputs are combined in a polarization combiner and passed through a WDM into the EDF to pump it. The EDF is followed by the tunable filter, which sets the wavelength of the pulses that pump the signal fiber amplifier. A 70/30 coupler is used to couple out light from the ring-laser through one of the coupler's arms. Another arm is connected to the WDM (G&H), completing the ring.

At the operating pump wavelength (1536 nm) and a pulsed repetition frequency (PRF) of 5 kHz, the pulsed pump laser source did not show signs of strong ASE for 2 μs or longer pulses. By going to a lower than 5 kHz PRF or shorter pump pulses than 1 μs, it could lead to significant ASE, with, e.g., 5% of the output power or more residing between the pulses at 3 kHz PRF and 1 μs pulse duration. The pump and signal pulses are generated by a dual-channel function generator and the AOMs.

Note that the PRF is significantly higher than the inverse of the fluorescence lifetime of Er^{3+}. Therefore, although ASE may be significant, losses to spontaneous emission are relatively minor. The high-energy pump pulses go through the WDM (Lightel), which also helps to reduce any ASE from the pump-EDFA in the signal band and are subsequently absorbed by the signal fiber amplifier. The signal-EDFA is counter-pumped. The residual pump energy is outcoupled from the signal path by a second WDM (Lightel) in order to measure it and to protect the tunable laser source (TLS). High residual pump pulse energy (e.g., over 15% of the total pump pulse energy) is evidence that the signal fiber amplifier may be too short.

Considering a signal saturation fluence to be around 1 $\mu J/\mu m^2$ at a 1560 nm wavelength, then on a fiber with a 20-μm-diameter core, we could obtain 0.31 mJ of extractable energy approximately, assuming most of the erbium ions have a healthy fluorescence lifetime (~10 ms, no quenching) and with pump powers on the 100-mW level. However, given that the core-pumping system also needs to increase the quantum efficiency of the EDFA system, relying on a pump wavelength as close as possible to the signal wavelength (i.e., 1536 nm) is imperative to study the effects of quenching dynamics without having to worry about other nonlinear effects that may affect the system. Reaching over 100-mW level of pump powers at 1536 nm wavelengths is quite a challenge with the current equipment we had available at the time. In addition, while higher power is always good to achieve, it was not imperative to have it for the purposes of this article.

Figure 6 shows the pump pulse, which confirms the strong distortion of the shape as the pump pulse extracts energy from the erbium–ytterbium co-doped fiber amplifier (EYDFA). It is also worth mentioning that more than 95% of the total output energy remains within the pulse and continues to do so at energies below 25 μJ. Therefore, ASE (primarily occurring between pulses) is less than 5%. By using Eq. (4), the gain modulation between the leading edge and the trailing edge is ~1.48-Np, at the extracted energy of 20 μJ. This suggests that the saturation energy is ~13.5 μJ at the pump wavelength. However, the pump fiber is Er/Yb co-doped fiber, leading to different cross-sections compared to EDF. The calculated saturation fluence at 1536 nm (assuming an aluminosilicate host) is equal to ~0.093 $\mu J/\mu m^2$, which corresponds to an effective core area of the pump fiber equal to ~145 μm^2.

Next, we discuss the results on the following two different signal fibers:

(1) ORC fiber: FUT No. 3.
(2) Commercial fiber (Fibercore): I-12 (980/120) HC (FUT No. 4).

Depending on the characteristics of the fibers (including the pump fiber), a judicious selection of the pulse duration and PRF of pump pulses is required to maximize the performance of the pulse energy extraction from the signal fiber amplifier. Most effort in this investigation was spent on exploring this parameter space. In the process, the pump pulses extract energy from the pump fiber and transfer it to the signal fiber amplifier. In the pulse pumping system, when the pump pulses pass through the signal fiber amplifier, at the beginning of each pulse, the excitation level in the signal fiber rises quickly, then suffers a sudden short loss of excited ions at the end of the pump pulse as any short-lived (quenched) ions relax. After that, the excitation decreases more slowly as normal ions relax. The signal pulse should arrive before most of the fast relaxation has occurred. When the next pump pulse arrives, the excitation levels will quickly rise once again, repeating the process.[29]

Diagnostics for this work include an optical spectrum analyzer (OSA, ANDO AQ6317B), a 1-GHz oscilloscope (Agilent DSO9104H), and InGaAs photodetectors (Thorlabs DET10C, 35-MHz, and EOT ET-3500, 15-GHz). Pulse energies are determined from the average power, and oscilloscope traces and spectra are checked for inconsistencies (e.g., excessive ASE) with the OSA in CW and different pulsed measurement modes. Average optical powers were measured with thermal and semiconductor power meters.

Experimental layout: FUT No. 3

The first selected fiber under test, FUT No. 3, EDF, is fabricated in the ORC. The fiber has a core diameter of 14.4-μm, a 0.13-NA aluminosilicate core centered in a 125-μm-diameter cladding, which was coated by a high-index polymer. The core absorption reached 130 dB/m at the 1530-nm peak. V = 3.84 at 1530 nm, so the fiber is multimoded.

In this section, the performance of in-band pulsed core-pumping of a fiber with a high degree of quenching is shown. The estimated erbium doping concentration of FUT No. 3 is 5.65 $\times 10^{25}$ m^{-3}, calculated through Eq. (5), and with an estimated absorption cross section [σ_{abs} (1530 nm) = 5.3 $\times 10^{-25}$ m^2]. The advantages presented for FUT No. 3, in the context of this research, lie in the large core area, sufficient to avoid nonlinear effects and also lead to higher extractable energy and saturation energy on the FUT. In addition to this, the fiber has a 130 dB/m core absorption at 1530 nm. Figure 7 shows CW unsaturable absorption measurements at 1536 nm.

Based on experimental data for different fiber lengths and signal wavelengths, a signal wavelength of 1565 nm and a fiber length of 0.17-m are selected. The summary of the research regarding the

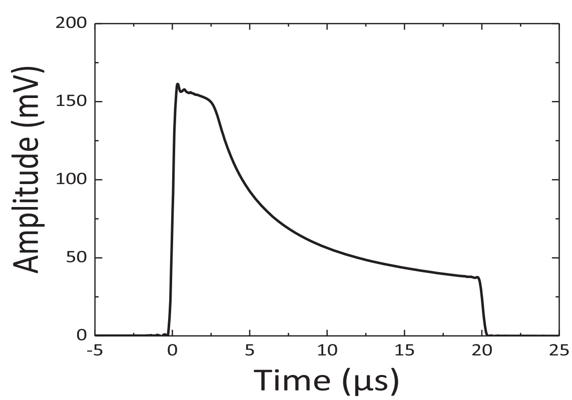

FIG. 6. Temporal trace of the stored pump pulse at 20 μJ energy, 20 μs pulse duration, and 5 kHz repetition rate [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

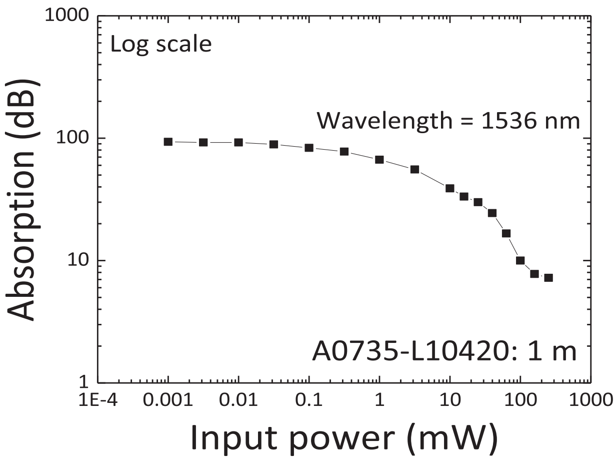

FIG. 7. Unsaturable absorption measurements from FUT No. 3 (log-scale) [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

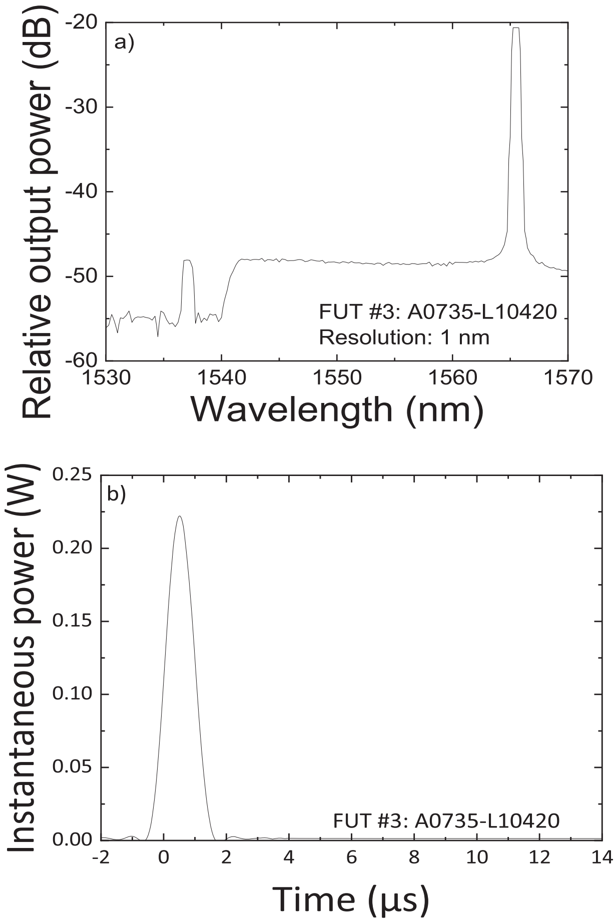

FIG. 8. (a) Optical spectra from the signal pulses at 1 μs, 5 kHz, and output pulse energy of 224 nJ. (b) Temporal trace from the signal pulses.

core pulse-pumping in highly doped EDF using the FUT No. 3 is presented in Fig. 8.

The counter-directionally core-pumped amplifier configuration used pump pulses at 25 μJ pulse energy, 25 μs pulse duration, and signal pulses at 162 nJ pulse energy, 1 μs pulse duration, both at 5 kHz PRF, which is the highest signal pulse energy achievable. Through the pulse generator, it was possible to control the position of the signal pulse, moving it through the pump pulse.

The experimental data show that the signal pulse extracts the energy more efficiently at the beginning of the pump pulse, decreasing by a factor of 0.02 mW when the signal pulse moves farther away from the leading edge of the pump pulse. The reason for the lower performance as the signal was shifted from the leading edge of the pump pulse is likely to be the higher instantaneous pump power in the leading edge. This also implies that the pump pulse duration is too long, i.e., better results may be achievable with shorter pump pulses with higher peak power.

Note also that the 25-μs pump pulse duration is much larger than the transit times through fiber. This is ~5 ns/m. For 1-μs pulse durations, the length of cables, fibers, and beam paths can normally be neglected, but for durations below 100 ns, this is not necessarily the case. In addition, higher signal pulse durations will cause a higher overlap between the pump and the signal pulses, leading to nonlinear effects and stronger concentration quenching detrimental effects.

The highest peak signal power measured is ~225 mW, corresponding to a pulse energy of 225 nJ, shown in Fig. 8. 20% of the pump energy is leaked from the FUT No. 3. This means that roughly 20 μJ of energy was stored within the fiber. Figure 9 shows the results at a constant 20 μJ stored pump energy at different avg. seed power levels, with a 5 kHz PRF, comparing these results with the CW-regime (i.e., avg. signal input power = CW signal input power).

In conclusion, the results have shown that in this highly quenched EDF, pulse-pumping is more efficient than CW-pumping (if only marginally in this case). The system obtained a 1.45 dB gain by pulse-pumping a 0.17-m EDF, compared to 0.6 dB with CW-pumping. Unfortunately, it seems that the detrimental effects on a highly quenched EDF were more severe than anticipated, at least with the pump pulse duration considered here.

We expected the large core of the FUT No. 3 and the short length to help mitigate the nonlinear effects and increase the saturation energy, resulting in higher stored energy and better gain efficiency. From Fig. 8, we can observe that the system does not show any evidence of nonlinear effects (i.e., ASE or FWM). Therefore, the design succeeded in that regard, but the poor gain and energy extraction of the system are evidence that we still could not avoid the detrimental effects of concentration quenching, even with pulse-pumping.

Due to the absence of other detrimental effects, one can conclude that the quenching dynamics has shortened the effective lifetime of most of the excited ions, to the point where even 1-μs pulses are unable to extract the stored energy fast enough, thus reducing the expected gain of the EDFA. Moreover, in the context of pump energy, assuming the stored energy in the fiber is 20 μJ, yet only

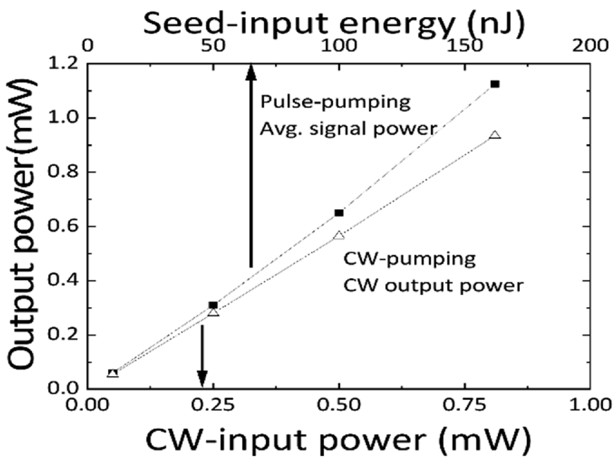

FIG. 9. Gain vs pump energy at 10-μs pulse and CW-power. In the case of pulse pumping, the pulses have a 25-μs pulse duration and a 5-kHz PRF, at a fixed stored pump pulse energy of 20 μJ. The seed-input pulse extracts the energy at the very end of the pump pulse energy, minimizing the overlap between the pump pulse duration and the signal pulse only, not the CW-signal.

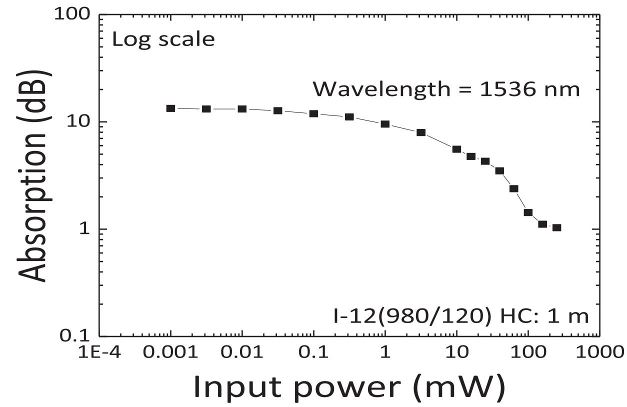

FIG. 10. Absorption measurements from the FUT No. 4 (log-scale) [Reprinted with permission from Pablo G. Rojas Hernández, "Study of partly quenched highly erbium-doped fibre amplifiers," Doctoral thesis, University of Southampton, UK, 2019, p. 123. Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license].

~1.13% of said energy is being extracted, the question now becomes if it is worth it to work with a large core area. Using a smaller core area will limit the saturation energy on the fiber, which in turn limits the extractable energy that can be achieved from it. However, using a larger core increases the pump threshold in the fiber, which means that higher pump energy will be needed to achieve gain in the signal fiber amplifier (i.e., FUT). Therefore, if it is not possible to improve the pump energy, then the easier way to address this is to reduce the core size of the signal amplifier.

To verify that it is possible to reach high gain with this pulse-pumping setup, we, therefore, next investigated a smaller-core EDF with low quenching, i.e., FUT No. 4, which is a commercial fiber, and used that as a baseline from which the impact of quenching could be assessed.

Experimental layout: I-12 (980/120)HC (FUT No. 4)

The second FUT, No. 4, is a commercial fiber I-12 (980/125) HC, fabricated by Fibrecore, which has a core diameter of 5.2-μm, a 0.25-NA aluminosilicate core centered in a 125-μm-diameter cladding, coated by a high-index polymer. The core absorption reached 20 dB/m at the 1530-nm peak. FUT No. 4 is investigated by the counter-, core-pumping scheme (as described in Fig. 5). Due to the low absorption peak at the pump wavelength (i.e., 1536 nm) as seen in Fig. 10, the operating fiber length is ~14.5 m in order to keep the same operating pump absorption as FUT No. 3 (i.e., 80%). The estimated Er-concentration from the FUT No. 4 is 8.7 $\times 10^{24}$ m^{-3}, calculated by Eq. (5). The saturation energy for FUT No. 4 is calculated to be 6.23 μJ, which is 7 times smaller than the FUT No. 3.

At 14.5 m fiber length, the pump leakage measured from the FUT No. 4 was 20%, which seems to indicate that the stored energy within the fiber is the same as the stored energy in FUT No. 3

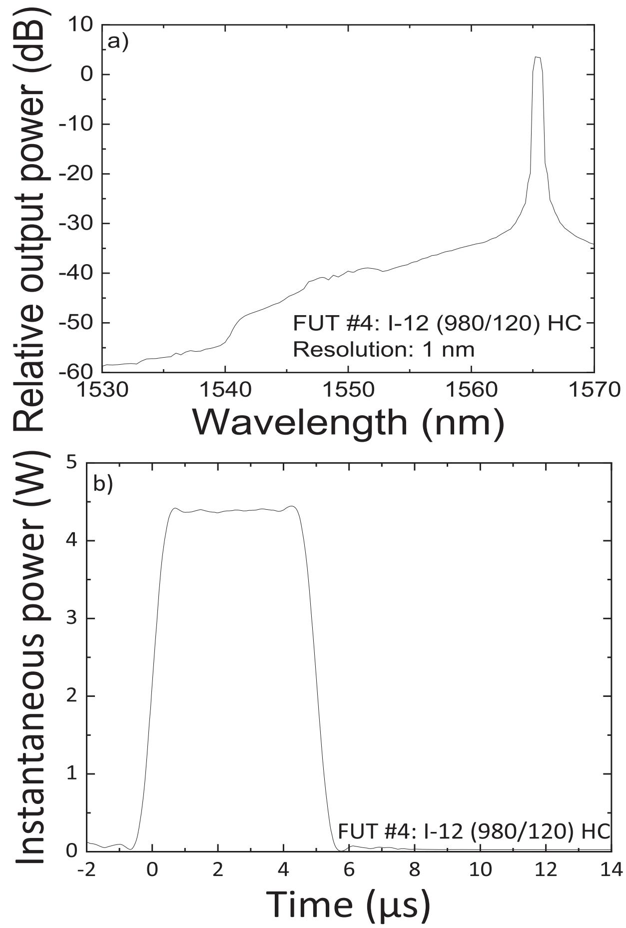

FIG. 11. (a) Optical spectra from the signal pulses at 5-μs, 5-kHz and output pulse energy of 13.5-μJ. (b) Temporal trace from the signal pulses.

TABLE I. Full review of the experimental results with different FUT.

Notes (case)	FUT No. 1	FUT No. 2	FUT No. 3	FUT No. 4
Core diameter	20 μm	45 μm	14.4 μm	5.2 μm
Core absorption at 1530 nm	95 dB/m	36 dB/m	130 dB/m	20 dB/m
Fiber type	Cladding	Cladding	Core	Core
Fiber length	0.2 m	0.5 m	0.17 m	14.5 m
Seed pulse energy	CW	CW	0.16 μJ	0.16 μJ
Signal pulse duration	CW	CW	1 μs	1 μs
Pump pulse duration	CW	CW	25 μs	25 μs
PRF	CW	CW	5 KHz	5 KHz
FUT output pulse energy	CW	CW	0.225 μJ	13.5 μJ
Resulting energy gain in FUT	CW	CW	1.45 dB	18 dB
Energy gain per unit length	CW	CW	8.4 dB/m	1.31 dB/m
FUT pump power	1.1 W	1.1 W	25 μJ	25 μJ

(i.e., 20 μJ). Furthermore, Fig. 11 shows the optical spectrum (a) and temporal traces (b) using pump pulses at 25 μJ pulse energy, 25 μs pulse duration, and signal pulses at 170 nJ pulse energy, 5 μs pulse duration, both at 5 kHz PRF. This amplifier configuration reached up to 13.5 μJ of output energy, which is 2.17 times the estimated saturation energy from the FUT No. 4 and corresponds to a pump energy conversion efficiency of 54%.

The signal energy is fixed at 170 nJ pulse energy in order to make a fair comparison between the FUT No. 3 and FUT No. 4. Shorter pulses at 1 μs, as well as changing the relative timing between the pump and signal by 0.1–0.5 μs, were also tested but did not show any significant difference in regards to the extractable energy.

To reiterate, the aim of this EDFA system is to convert pump energy to signal energy, and in order for this to succeed, the first step is to launch the pump pulse energy into the signal fiber amplifier and then extract that energy with the signal pulses. However, there is a limit to how much pump energy one can store within the signal fiber amplifier. Saturation energy is one of the main factors that determines the limit of the stored energy, which in turn depends on the core area. Therefore, Figs. 8 and 11 show that the FUT No. 3 can have much higher stored energy capacity compared to the FUT No. 4. Nevertheless, the pump pulse energy currently available (i.e., 25 μJ pump pulse energy) can still be fully stored within the commercial fiber, and because of that, there is no need for such a high saturation energy provided by the FUT No. 3.

In other words, there is a limit to how much energy can be stored within both signal fiber amplifiers, but because it is not possible to reach that limit in the case of the FUT No. 3, that advantage becomes irrelevant. Rather, in this situation, the ability to store more energy may be a disadvantage, since it means that the pump energy needed to reach a certain gain becomes higher, and, equivalently, the gain achieved for a certain pump energy becomes lower.

Therefore, it is not possible to create as much gain on the FUT No. 3 (even disregarding the quenching). This makes it harder to extract the energy from it, compared to FUT No. 4. One can observe a full review of the experimental results shown and discussed in this paper in Table I.

CONCLUSION

In summary, by using the same counter-directionally core-pumped amplifier configuration and retaining the same stored pump energy (20 μJ) for both cases, we have shown the comparison in performance from two different fibers, a highly doped, homemade erbium fiber (FUT No. 3) and a low concentration, commercial erbium fiber (FUT No. 4).

The FUT No. 3 achieved a pulse energy output of 0.225 μJ, as shown in Fig. 8, Assuming that ~20 μJ of energy was stored within the fiber in the CW-regime, we managed to extract 0.9% of the stored energy, 0.38% of the saturation energy within the FUT No. 3, as well as 0.73% pump conversion efficiency. In the pulse-regime, the 1 μs signal pulses managed to extract ~1.13% of the stored energy. This translates to 0.5% of the saturation energy and 0.9% pump conversion efficiency.

The FUT No. 4 had a fiber length of 14.5 m to make sure that the stored energy within the fiber is the same as the stored energy in FUT No. 3 (i.e., 20 μJ). In the pulse-regime, the 1 μs signal pulses managed to extract 67.5% of the stored energy. This translates to 216.7% of the saturation energy and 54% pump energy conversion. Unlike FUT No. 3, this fiber did not show any improvement between the CW- and pulse-pumping regime, and even longer or shorter pulses did not show any changes in their performance, which is expected from a low concentration erbium fiber.

One can observe that the absorbed pump pulse energy is insufficient to fully exploit the upper limit of stored energy given by the signal fiber core area. In addition, unfortunately, FUT No. 3 is still taking the penalty of having a harder time extracting the energy from that fiber due to quenching dynamics.

Much better results were shown by the commercial fiber (i.e., FUT No. 4). In this regard, the FUT No. 4 was a better match to the system than the FUT No. 3. The results demonstrate the efficacy of pulse pumping when the parameters of the FUT and pump source are appropriate.

Our results demonstrate that the efficiency of the signal fiber amplifier with high-doping concentration is directly linked to the lifetime in which the ions suffer from energy transfer upconversion (i.e., quenching dynamics). Benefits of pulse-pumping, amplifier configuration of a highly quenched erbium doped fiber (i.e., FUT No. 3) were demonstrated by reaching a signal gain (i.e., 1.45-dB) 2.4 times higher through pulse-pumping compared to CW-pumping. The results also demonstrate the efficacy of pulse pumping when the parameters of the FUT and pump source are appropriate.

In the context of pulse duration, one needs to remember that this commercial fiber will not suffer from concentration quenching as much as a highly doped fiber, so it is easier to avoid this detrimental effect, even at longer pulses (e.g., above 5 μs). The primary idea is to overcome concentration quenching by using short pump pulses to store the energy efficiently within the fiber before the Er^{3+}-ions are quenched, and their lifetime is reduced, reducing the gain of the signal fiber amplifier. Therefore, a highly doped fiber does require short pump pulses, whereas the commercial fiber does not necessarily require that.[31] Therefore, one can conclude that the pump pulse energy and the core area need to be reasonably well matched. In this regard, FUT No. 4 was a better match to the core-pumping system than FUT No. 3. Despite that, the FUT No. 3 still outperforms the unquenched EDF in the generation of gain per unit length (>8.4 dB/m), which is 6.4 times higher than the FUT No. 4.

Additionally, with the highest achievable output pulse energy from a counter-directionally cladding-pumped amplifier configuration on a highly doped erbium fiber, their highest gain per unit length was >5.9 dB/m at a 1560 nm signal wavelength. While certainly superior to other unquenched silica EDFs by a significant margin (e.g., Refs. 1 and 12), the FUT No. 3 still has 1.4 times higher gain per unit length,[31] both systems operating at 2 μs pump pulse duration.

With better optimization of the pulsed-pumping source, our core-pumping configuration could counteract quenching effects and outperform cladding-pumping systems in terms of gain per unit length and energy per unit core area and length, even though core-pumping is limited to W-level pump powers. However, increasing the pulsed-pumping source for a core-pumping configuration at an uncommon pump wavelength (e.g., 1535 nm) would require significantly more effort and investment. This would undermine the goal of developing a simpler and cheaper amplifier configuration compared to the previously discussed double-clad, highly doped erbium-doped fiber amplifier. As such, our experimental analysis of quenching dynamics presented here not only highlights an approach for scaling pulse energy using shorter fiber lengths for mitigating nonlinear effects but also provides valuable insights into quenching-influenced gain behavior in fiber amplifiers.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Pablo G. Rojas Hernandez: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (lead); Validation (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (lead). **Shankar Pidishety**: Conceptualization (lead); Data curation (supporting); Formal analysis (supporting); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (supporting); Supervision (supporting); Validation (lead); Visualization (lead); Writing – original draft (supporting); Writing – review & editing (equal). **Johan Nilsson**: Conceptualization (lead); Data curation (lead); Formal analysis (equal); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (equal); Supervision (lead); Validation (lead); Visualization (lead); Writing – original draft (supporting); Writing – review & editing (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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