



HIGH ENERGY SHORT LASER PULSES USING A LARGE MODE AREA GAIN FIBER AT 1530 NM WAVELENGTH

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ABSTRACT

We numerically obtain the high energy short duration pulses using an Erbium-doped specialty fiber of $\sim 1700 \mu\text{m}^2$ effective mode area and $\sim 25 \text{ dB/m}$ gain around 1530 nm wavelength. We investigate propagation of the Gaussian shaped nanosecond and picosecond pulses and observe the amplification of the pulses due to the high gain of the medium. We achieve the pulses of $\sim 14 \text{ mJ}$ energy, 127.6 ns duration, and $\sim 112 \text{ kW}$ peak power by the amplification of $10 \mu\text{J}$ energy, 10 ns duration, and 1 kW peak power pulses in 1 m long large mode area gain fiber. Also, we obtain the pulses of $\sim 2.8 \text{ mJ}$ energy, 107.6 ps duration, and $\sim 26 \text{ MW}$ peak power by the amplification of $1 \mu\text{J}$ energy, 10 ps duration, and 100 kW peak power pulses while propagating in 1 m length of the same fiber. These high energy pulses in eye-safe regions can be useful in eye-safe remote sensing, and 3D laser processing of silicon.

KEYWORDS: Large mode area fiber, Erbium-doped fiber, Gain Fiber, Pulse amplification, Short laser pulses.

INTRODUCTION

Over past few years, rare-earth elements doped gain fiber lasers and amplifiers become the research interest due to their wide range of applications [2, 3]. Among these doped fibers, Erbium-doped fibers (EDFs) attracted attention due to their operation in the eye safe region and atmospheric transparency window around $1.5 \mu\text{m}$ wavelength which make them useful in various fields like in medical for cancer treatment, cornea surgery, and burn treatment, in defense for detection of explosives, distance interrogation, diagnostics, and in micro-machining for cutting, welding and drilling [1]-[5]. But the development of cost-effective high power ultrafast Er-doped sources is a challenging task. Power scaling faces various issues including thermal effects, nonlinearity, and large quantum defects for standard 980 nm pumping [6]. Despite these limitations, a lot of work has been done in the direction to developed Er-doped fiber lasers since they have fascinating applications which outperform Yb-doped fibers. For example, multi-photon polymerization using second harmonics of Er-

doped fiber laser, eye-safe remote sensing, and 3D laser processing of silicon [6]-[11]. Desmoulins et al. presented large core Er-doped fiber amplifier and generated pulses of 1.1 ns with 1.4 mJ energy at 1567 nm wavelength [12]. Kotov et al. reported amplification of 100 ns pulses to energy as high as 1 mJ using Er-doped fiber laser at 1560 nm wavelength [13]. Zhao et al. demonstrated a 1553 nm Er-doped fiber master oscillator power amplifier laser system to generate pulses of 5 ns duration, 210 μJ energy, and 40 kW peak power [14]. Nicholson et al. reported generation of ultra-short pulses of 541 μJ energy using a very large mode area Er-doped fiber amplifier at 1572.3 nm operating wavelength [15]. Dvoyrin et al. reported generation of 3.5 ns, 4 kW peak power pulses with 14 μJ energy by using a two-stage diode pumped Er-doped fiber amplifier operating at wavelength of 1550 nm [16]. Lee et al. demonstrated generation of single

frequency optical pulses of duration 510 ns and 3.5 kW peak power pulses with 1.8 mJ energy using Er-Yb co-doped silicate glass fiber amplifier at 1572 nm wavelength [17]. Recently, Joshua et al. achieved 3 mJ energy with 21.5 ns pulses duration at 1550 nm wavelength [18]. Sobon et al. amplify the Gaussian pulses of 250 ps, 6 pJ energy pulses with ~0.25 mW average power to sub-picosecond pulses of 0.88 ps, 0.95 ps, and 1.05 ps with 2 μJ energy and with maximum output peak power ~2MW in large mode area Er- & Er/Yb doped fibers by using CPA system at 1555 nm wavelength [19]. Our group also recently presented the amplification of pulses using EDF and achieved ~65 ps duration pulses with ~1.7 mJ energy at 1530 nm wavelength [20].

In this work, we numerically demonstrated the amplification of short duration (ns and ps) pulses and achieved pulses of up to ~14 mJ high energy using 1 m long large mode area (LMA) EDF at 1530 nm wavelength. The area of the chosen fiber is ~1700 μm² and the maximum gain is ~25 dB/m by considering pumping at 980 nm wavelength. Here, the Gaussian shaped pulses of 10 ns duration, 1 kW peak power, 10 μJ energy amplified to 127.6 ns duration, 112 kW peak power, ~14 mJ energy pulses while 10 ps duration, 100 kW peak power, 1 μJ energy pulses amplified to 107.6 ps duration, 26 MW peak power, ~2.8 mJ energy after propagating 1 m length of the LMA-EDF.

NUMERICAL SIMULATIONS

We have carried out the numerical simulations on solving the nonlinear Schrodinger equation included gain term by using split-step Fourier method [21]-[23]. The nonlinear equation is given by

$$\frac{\partial A(t,z)}{\partial z} = \left(-i \frac{\beta_2}{2} \frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3}{\partial T^3} + i\gamma \left(|A|^2 + \frac{i}{\omega_0} \frac{1}{A} \frac{\partial}{\partial T} (|A|^2 A) - T_R \frac{\partial |A|^2}{\partial T} \right) + g_0 \Omega_\omega \Omega_t \right) \quad (1)$$

Where A represents the amplitude of slowly varying envelope of the pulse, $\beta_2 (= 2.70 \times 10^{-26} \text{ s}^2/\text{m})$ and $\beta_3 (= 1.49 \times \frac{10^{-40} \text{ s}^3}{\text{m}})$ are the second and third order dispersion coefficients of the fiber, respectively. The parameters γ , ω_0 , and T_R denote the nonlinear coefficient, central frequency, and Raman response time, respectively. Here, g_0 is known as gain coefficient while g is the gain which depends on both time and frequency. Ω_ω and Ω_t represent the gain saturation and gain narrowing, respectively of the following mathematical forms [22].

$$\Omega_\omega = \exp\left(-\frac{\omega^2}{\Delta\omega_g^2}\right), \text{ and } \Omega_t = \frac{1}{\left(1 + \frac{|A(z,t)|^2}{P_{sat}}\right)} \quad (2)$$

Where $\Delta\omega_g$ and P_{sat} are representing gain bandwidth and the saturation power, respectively.

Equation (1) can be written in the form of dispersion, nonlinearity, and gain operators as following [22], [23]:

$$\frac{\partial A(t,z)}{\partial z} = (\hat{D}(\omega) + \hat{N}(t) + \hat{G}(\omega, t))A \quad (3)$$

$$\text{Where, } \hat{D}(\omega) = -i \frac{\beta_2}{2} \frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3}{\partial T^3}$$

$$\hat{N}(t) = i\gamma \left(|A|^2 + \frac{i}{\omega_0} \frac{1}{A} \frac{\partial}{\partial T} (|A|^2 A) - T_R \frac{\partial |A|^2}{\partial T} \right)$$

$$\text{and } \hat{G}(\omega, t) = g_0 \Omega_\omega \Omega_t$$

We used the model given by G. Gao et al. to solve the above NLSE which includes gain term by split-step Fourier method [22], [24]. The schematic of the simulation sequences along with the steps for pulse amplification is shown in Fig. 1.

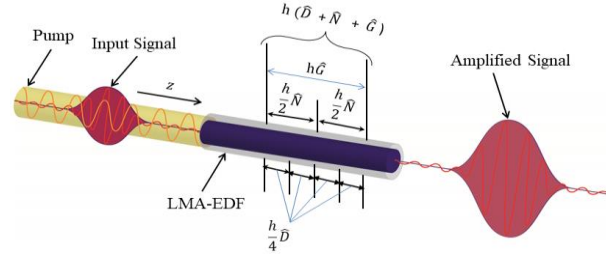


Fig. 1. Schematics depict the simulation sequences and steps for pulse amplification.

The approximate solution of the equation (3), using split step Fourier method, can be written in terms of exponential operator as

$$A(z + h, t) = \exp\langle h\hat{D} \rangle \exp\langle h\hat{N} \rangle \exp\langle h\hat{G} \rangle A(z, t) \quad (4)$$

The consequences of $\exp\langle h\hat{D} \rangle$ and $\exp\langle h\hat{N} \rangle$ operators are very well-known [24]. We have used the following definition of the exponential gain operator

$$\exp\langle h\hat{G} \rangle A(z, t) = F_T^{-1} \{ \exp[hG(t, \omega)] F_T[A(z, t)] \} \quad (5)$$

$$\approx F_T^{-1} \left\{ \left[1 + hG(t, \omega) + \frac{h^2 G^2(t, \omega)}{2} \right] F_T[A(z, t)] \right\}$$

$$= A(z, t) + \frac{hg_0}{2} F_T^{-1} \{ \Omega_\omega(\omega) F_T[A(z, t)] \} + \frac{h^2 g_0^2}{8} \Omega_t^2(t) F_T^{-1} \{ \Omega_\omega^2(\omega) F_T[A(z, t)] \} \quad (6)$$

Where h is the small step size in the propagation direction and F_T and F_T^{-1} are correspond Fourier and inverse Fourier transformations. We have used the symmetrical split-step Fourier method to solve this NLSE with gain term of the following form

$$A(z + h, t) = \exp\langle \frac{h}{4} D(\omega) \rangle \exp\langle \frac{h}{2} N(t) \rangle \exp\langle \frac{h}{4} D(\omega) \rangle \exp\langle hG(t, \omega) \rangle$$

$$\exp\langle \frac{h}{4} D(\omega) \rangle \exp\langle \frac{h}{2} N(t) \rangle \exp\langle \frac{h}{4} D(\omega) \rangle A(z, t) \quad (7)$$

RESULTS AND DISCUSSIONS

Here, the utilized fiber is a few mode LMA fiber with diameter and effective mode area of $60 \mu\text{m}$ and $\sim 1700 \mu\text{m}^2$, respectively which supports LP_{01} and LP_{11} modes. The single mode operation is accomplished by using a suitable mode spacing between them [20]. We considered the doping of Er^{3+} with concentration of $1.2 \times 10^{25} \text{m}^{-3}$ in the core of the fiber. The maximum gain achieved of $\sim 25 \text{dB/m}$ by considering the pumping at 980nm wavelength. We numerically simulated the propagation of nanosecond and picosecond duration pulses by solving the gain included NLSE using split-step Fourier method.

A. Amplification of nanosecond pulses

We numerically simulated the propagation of nanosecond duration of pulses in 1m long LMA-EDF around 1530nm wavelength. First, we calculate the pump power for the maximum amplification of Gaussian pulse of 1kW input peak power, 10ns duration, and $10 \mu\text{J}$ energy. We have varied the pump power from 20W to 180W and plotted the variations of the parameters of output pulses: output pulse width, output peak power, and output pulse energy as shown in Fig. 2.

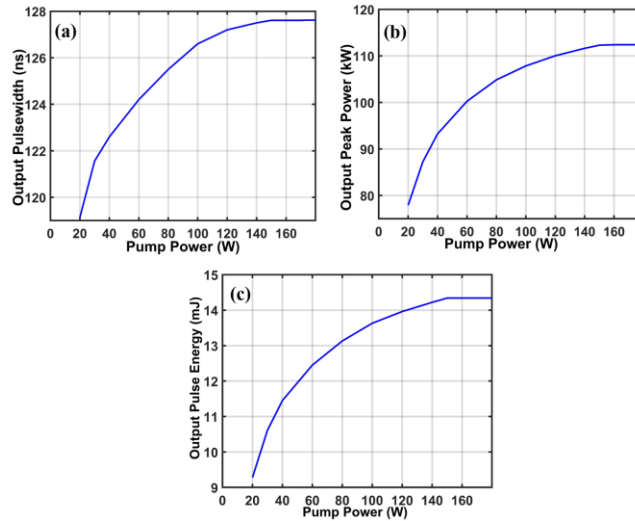


Fig. 2: Variation of (a) Output pulse width, (b) Output peak power, and (c) Output pulse energy with pump power.

Here, we can see that all the three parameters of output pulses increase with increasing the pump power up to for ~150 W pump power and saturates beyond it. Therefore, we consider 150 W pump power for the maximum amplification of nanosecond pulses. Now, we numerically demonstrated the propagation of 1 kW input peak power and 10 ns duration pulses pumped with 150 W power at 1530 nm wavelength. The temporal profile of the output pulses, contour plot, and the evolution of the pulse along the 1 m length of LMA-EDF are shown in Fig. 3 (a), 3 (b) and 3 (c), respectively.

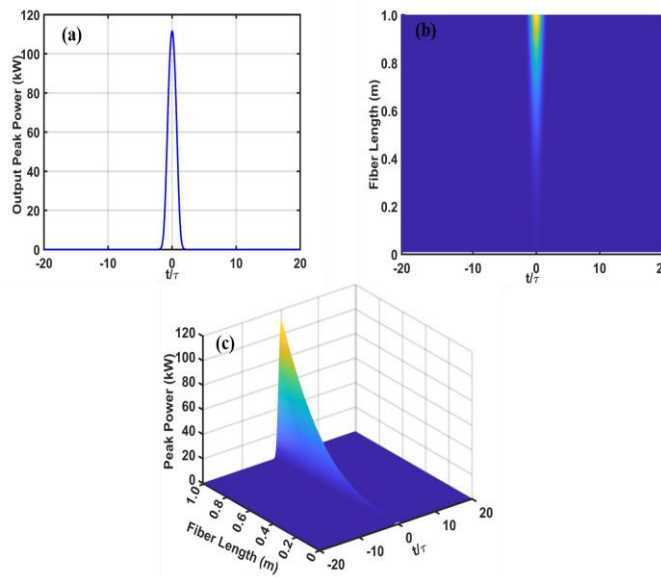


Fig. 3. Gaussian Pulses at 1m long fiber at 140 W Pump power (a) Temporal profile of the output pulse (b) Corresponding Contour Plot (c) Pulse evolution through the fiber.

Here, one can see that with the length of the fiber the pulse broadens and amplifies as well. We could see the pulse amplification due to gain medium, which is Erbium in our case, and broadening because of the significant dispersion. The peak power, pulse width and energy of the achieved output pulse are around 112 kW, 128 ns, and 14 mJ, respectively. Here, the amplification is around 112 times of the input peak power.

Hence, the fiber can be used to amplified short pulses (nanosecond) with pump powers and depending on the commercial availability of the pump source which can be used to achieve mill joules energy of the nanosecond duration pulses.

B. Amplification of picosecond pulses

We have also studied the amplification of picosecond pulses in 1 m length of the high gain LMA-EDF (same fiber used in nanosecond pulse amplification) at 1530 nm Wavelength. In order to optimize the pump power for maximum pulse amplification, we have fixed the input peak power of Gaussian shaped 10 ps duration pulse to 100 kW and checked the variations of output pulse width, output peak power, and output pulse energy for the pump power ranging from 20 W to 180 W in 1 m (fixed length) long LMA-EDF which is shown in Fig 4 (a), 4(b), and 4(c), respectively. It can be clearly seen that all the three parameters of output pulse are increasing on increasing the pump power and start saturating around 150 W pump power. Therefore, we have chosen 150 W as the optimized value of pump power for maximum pulse amplification up to ~26 MW output peak power.

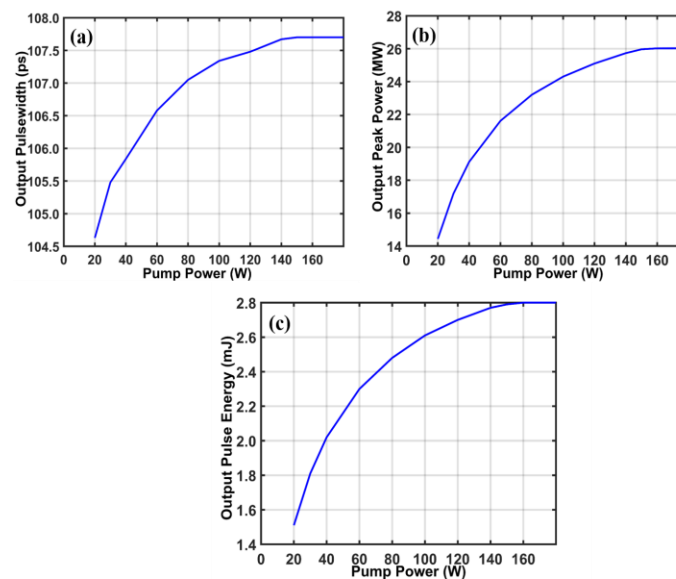


Fig. 4. (a) Variation of Pulse width with pump power (b) Variation of peak power with pump, and (c) Variation of pulse energy with pump power.

Now, we have numerically considered the propagation of 1 ps, 100 kW input peak power pulse in 1 m long LMA-EDF pumped with 150 W power at 1530 nm wavelength. The temporal profile of output pulse, the contour plot, and evolution of the pulse along the length of the fiber are shown in Fig. 5(a), 5 (b), and 5 (c), respectively. We could observe the pulse amplification which is caused by the interaction of nonlinearity, gain, and dispersion in the fiber. We have achieved more than 26 MW peak power with ~108 ps pulse duration at 150 W pump power. This is around 260 times amplify with respected to the input pulse.

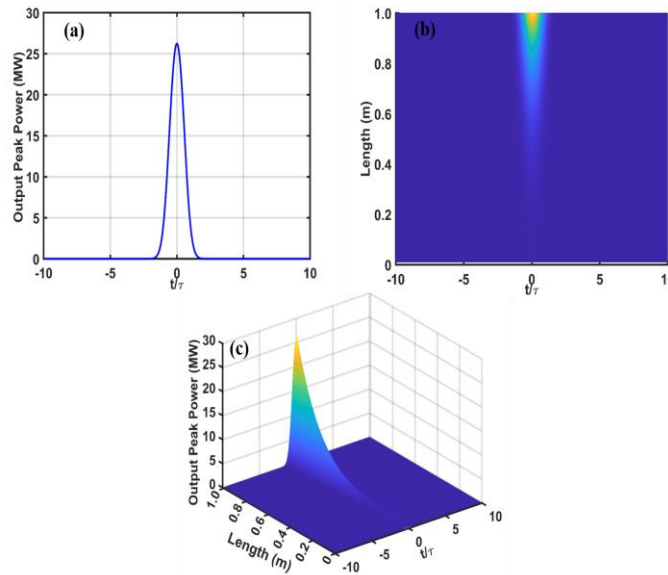


Fig. 5: Propagation of 10 ps, 100 kW Gaussian pulse through 1 m length of EDF. (a) Temporal profile at output end (b) Contour Plot (c) Pulse evolution along the length.

Hence, we can conclude that peak power input is broaden due the dispersion of the medium along with amplification due to the doping of Erbium ion in the core of LMA fiber.

CONCLUSION

We have numerically demonstrated the amplification of nanosecond pulses through large mode area ($\sim 1700 \mu\text{m}^2$) erbium doped fiber at 1530 nm wavelength. We observe the amplification of 10 ns, 1 kW pulse of 10 μJ energy to 127.6 ns, ~ 112 kW peak power pulse about 14 mJ energy while propagating through 1 m long large mode area fiber. Also, we have studied the propagation of picosecond pulses in 1 m length of the same fiber and observed broadening and amplification of 10 ps pulses with 100 kW input peak power with 1 μJ to 107.6 ps pulses, more than 26 MW peak power with 2.8 mJ energy pulses. The amplified pulses can be useful in eye-safe remote sensing, and 3D laser processing of silicon.

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