Numerical study of a hybrid mode-locked erbium-doped fluoride fiber laser at 2.8 μm

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Abstract. We numerically investigate a hybrid mode-locked erbium-doped fluoride fiber laser in the mid-infrared region. Based on the coaction of nonlinear polarization rotation (NPR) and semiconductor saturable absorber mirror (SESAM), uniform mode-locked soliton pulse with 155 fs pulse duration, 14.78 kW peak power, and 2.29 nJ pulse energy can be achieved. For comparison, the single SESAM mode-locking and NPR mode-locking of the erbium-doped fluoride fiber laser are simulated, respectively. The effect of all kinds of parameters including gain fiber length, saturable energy of the gain fiber, linear cavity phase delay bias, and small-signal gain on the hybrid mode-locking laser are also investigated.

1. Introduction

Tremendous potential applications of ~3 μm ultrafast laser sources for the military, minimally invasive surgery, and mid-infrared molecular spectroscopy have moved the mid-infrared ultrafast laser to a hot research subject [1-3]. Among these laser sources, high concentration erbium-doped fluoride fiber lasers possessing the excellent properties of high efficiency and broad spectral emission waveband, are believed to be one of the most attractive candidates for achieving mid-IR laser at ~3 μm [4-6].

Generally, the attractive alternative method to obtain the ultrashort pulse is passively mode-locked technology. These technologies generally are divided into three types. The first type is the true saturable absorber (SA) based mode-locking, that is, the laser is modulated by a SA, such as SESAMs [7-9], graphene [10-12], and some other nonlinear optical materials [13-23]. This type of technology can easily realize the self-started mode-locking owing to the SAs’ low saturation intensity. Nevertheless, the true-SA based mode-locking of the fluoride fiber laser can hardly obtain the femtosecond-scale ultrashort pulse due to relatively low modulation depth. As far as we know, all the results achieved in the experiments for these fluoride fiber lasers are only on the picosecond-scale [7-9, 12, 21, 22]. Moreover, the material SAs normally have a relatively low damage threshold as well as a short life-time, which also hinders the laser operated in a high energy regime. The second type is artificial-SA based mode-locking, and the most typical representative of it is the nonlinear polarization rotation (NPR) technology [24-26]. As a Kerr-effect-based SA, NPR possessing the advantages of large modulation depth, fast response time, high damage threshold, as well as long-term stability, is beneficial for achieving ultrashort pulse laser with high energy and high stability. However, this technology faces the difficulty of self-starting from the continuous-wave operation because its mode-
locking initiation requires a high nonlinear effect [27-29]. The third type is hybrid mode-locking, which combines the former two types, enables the laser self-started mode-locking easily as well as operated in high energy and femtosecond-scale regime [30-34]. For the hybrid mode-locked technology, the current study is mainly focused on the ~1.5 μm and ~2 μm wavelengths [28, 29, 35-38]. As far as we know, there are no correlative results reported in the mid-IR region.

In our investigation, the numerical simulation of a hybrid mode-locked erbium-doped fluoride fiber laser at 2.8 μm is conducted. By placing a SESAM into the NPR ring cavity, uniform mode-locked soliton pulse with 155 fs pulse width as well as 79.2 nm 3 dB spectral width is demonstrated numerically. Correspondingly, the peak power is 14.78 kW, and the pulse energy is 2.29 nJ. For comparison, the single SESAM mode-locking and the NPR mode-locking of the erbium-doped fluoride fiber laser are simulated, respectively. In addition, the effect of all kinds of parameters including gain fiber length, saturable energy of the gain fiber, linear cavity phase delay bias, as well as small-signal gain on the output pulse characteristic of the hybrid mode-locking erbium-doped fluoride fiber laser are also researched.

2. Theoretical model

Figure 1 depicts the schematic configuration of the hybrid mode-locked erbium-doped fluoride fiber laser. This ring cavity is composed by an erbium-doped fluoride gain fiber, a SESAM, a wavelength division multiplexer (WDM), two collimators, as well as free space components which consist of a polarization beam splitter (PBS), wave plates (half-wave plate and quarter-wave plate) and a polarization-dependent isolator (PD-ISO). Although the fluoride-based WDM is not available on the shelf, it can still be replaced with a fluoride-based pump combiner in the experiment [39, 40]. The erbium-doped fluoride fiber used in the simulation is selected from Le Verre Fluore, which has a fiber loss lower than 0.04 dB/m at 2800 nm [26]. A laser diode which operating at 976 nm was selected as the pump source. After passing through the collimator 2, the polarization light is divided into two polarization components by the effect of PBS. The vertical component enters into the free space and is focused through the lens on the SESAM while the horizontal component acts as the output light. The SESAM from BATOP GmbH is chosen as the SA, which has 20% modulation depth, 10 ps recovery time, as well as 70 μJ/cm² saturation fluence [7]. The PD-ISO which is put behind the PBS also works as a polarizer as well as insures the light one-way operation in the ring cavity. The wave plates play a role in adjusting the polarization and birefringence of the cavity to optimize the mode-locking performance. When the polarization main axis of the waveplates is parallel to the polarization state of the middle of the pulse, the central part corresponding to the high intensity can pass the gain fiber while the marginal part with low intensity will be absorbed, thus the pulse becomes narrower, and the uniform ultrashort mode-locked pulse will be formed finally.

![Figure 1. Schematic configuration of the hybrid mode-locked erbium-doped fluoride fiber laser.](image)

To simulate the mode-locking, the pulse tracing technique is used. By using the coupled Ginzburg-Landau equations, we establish the hybrid mode-locked dynamic model of the laser, which takes the effect of dispersion, Kerr nonlinearity, and saturated gain with a finite bandwidth into account, and calculate these equations numerically with the split-step Fourier method [41]. The equations can be written as [38]:

\[
\text{Equations}
\]
where $u$ and $v$ represent the pulse normalized envelope along the two orthogonal polarization axis, respectively; $2\beta=2\pi\Delta n/\lambda$ is the wavenumber difference of the two modes, in which $L_b=\lambda/\Delta n$ is the beat length, and $\lambda$ is the operation wavelength; $2\delta=2\beta\lambda/(2\pi c)$ represents the inverse group velocity difference, in which the velocity of the light in the vacuum is denoted by $c$. $\gamma$ is the nonlinear coefficient. The second and third orders dispersion coefficient can be represented as $\beta_2$ and $\beta_3$, respectively; $g$ represents the saturation gain coefficient of the fiber, meanwhile, the gain bandwidth is expressed by $\Omega_g$. For the undoped fibers, $g=0$; for the erbium-doped fluoride fiber, the saturation gain can be represented as:

$$g = g_0 \exp\left(-\int \left(|u|^2 + |v|^2\right) dt\right)$$

Under this cavity structure, the saturable absorption of SESAM can be written as the following equation:

$$\frac{\partial \alpha_s}{\partial t} = -\alpha_s - \alpha_0 - \frac{|u|^2 + |v|^2}{F_{sat}}$$

where $\alpha_0$ represents the initial absorption of the absorber, $T_{rec}$ represents the recovery time of absorption, as well as the saturation energy of the SESAM is represented by $F_{sat}$. Here we would like to mention that the influence of SESAM’s dispersion on the mode-locking performance can be ignored, since the interaction length of the light with the SESAM is very short while the interaction is very long for the gain fiber. Moreover, the gain fiber also has a very large dispersion coefficient ($\beta_2=-86$ ps$^2$/km).

In the absence of SESAM, the nonlinear transmission $T_i$ in the laser ring cavity could be represented as:

$$T_i = \sin^2(\theta)\sin^2(\phi) + \cos^2(\theta)\cos^2(\phi) + \frac{1}{2}\sin(2\theta)\sin(2\phi)\cos(\phi_{wp} + \phi_F)$$

where $\theta$ and $\phi$ are the angles for the fiber fast axis with the polarizer axis and the analyzer axis, respectively. $\phi_{wp}$ represents the linear cavity phase delay bias which resulted from the PCs. $\Delta\phi_F$ is the phase delay originating from the gain fiber, which includes both the linear phase delay $\Delta\phi_{LB}$ and nonlinear phase delay $\Delta\phi_{NL}$. The expressions of the $\Delta\phi_F$, $\Delta\phi_{LB}$ and $\Delta\phi_{NL}$ are as follows:

$$\Delta\phi_F = \Delta\phi_{LB} + \Delta\phi_{NL}$$

$$\Delta\phi_{LB} = \frac{2n_0}{\lambda}(n_x - n_y) = \frac{2n_0}{L_b}$$

$$\Delta\phi_{NL} = \frac{2n_0(\Delta n_x - \Delta n_y)}{\lambda} = -\frac{\gamma(\sqrt{|u|^2 + |v|^2})\cos(2\theta)}{3}$$

where $n_x - n_y$ stands for the linear birefringence, $\Delta n_x$ and $\Delta n_y$ represent the nonlinear indexes of refraction, as well as $(|u|^2 + |v|^2)$ represent the laser power in the cavity. By solving Equations (4) - (7), the nonlinear transmission of the cavity could be obtained.

In our simulation, $g_0$ and $F_{sat}$ are used as the control parameters to describe the energy pumped into the gain fiber. Here, we neglect the fiber loss and the influence of the third-order dispersion for simplicity. The pulse evolution in the cavity starts from a random Gaussian noise signal, and the calculated results of the last cycle are used to be the input of the next round. The following parameters are used for the simulations: $\lambda_0=2800$ nm; $\beta_2=-86$ ps$^2$/km; $\gamma=0.167$ W$^{-1}$km$^{-1}$; $\Omega_g=110$ nm; output coupling rate OCR=0.2; $\theta=\pi/8$; $\phi=5\pi/8$. 
3. Simulation results and discussion

In this hybrid mode-locked fiber laser, uniform soliton mode-locking could be readily formed by setting the parameters $E_{sat}=2350$ pJ, $L_b=9.25$ m, $\phi_{wp}=1.1*\pi$, and $g_0=1.15$ m$^{-1}$.

![Image of Figure 2](image2.png)

**Figure 2.** Uniform hybrid mode-locked soliton output: evolution of the output pulse (a) and spectrum (b); Output temporal (c) and spectral (d) in the 400th round trip.

![Image of Figure 3](image3.png)

**Figure 3.** Uniform NPR mode-locked soliton output: evolution of the output pulse (a) and spectrum (b); Output temporal (c) and spectral (d) in the 400th round trip.

As shown in the Figure 2(a), we can see that the intensity of the output pulse does not change with the increase of round trips, indicating the mode-locked soliton pulse is uniform. The corresponding spectrum temporal evolution with round trips is presented in Figure 2(b). Figures 2(c) and 2(d) depict the output temporal profile as well as spectral profile of the 400th round trip of hybrid mode-locked erbium-doped fluoride fiber laser, respectively. From Figure 2(c) we can see the mode-locked pulse is hyperbolic secant shape with 155 fs pulse duration, and 14.78 kW peak power. As shown in the Figure 2(d), the corresponding 3 dB spectral bandwidth is 79.2 nm. The time-bandwidth product (TBP) is calculated to be 0.470, which is closed to the Fourier transform-limited (0.315), indicating the mode-locked pulse has a small chirp. There is an obvious Kelly side band in spectral profile, which indicates that it is a typical nonlinear Schrödinger (NLS) soliton mode-locking.
For comparison, we move the SESAM and NPR components out of the ring cavity sequentially. At first, we remove the SESAM and adjust the $\phi_{wp}$; the uniform NPR mode-locking can also be obtained. Figures 3(a) and 3(b) are present the pulse and spectrum evolution with round trips, respectively. Meanwhile, Figures 3(c) and 3(d) are the output temporal profile and spectral profile in the 400th round trip, respectively. The obtained pulse with 328 fs duration and 612.52 W peak power. The corresponding 3 dB spectral bandwidth is 34.68 nm, as well as the TBP is calculated to be 0.436. Meanwhile, compared with hybrid mode-locking, lower-intensity but more Kelly sidebands could be noticed in the spectral profile.

Afterward, we move out of the NPR component, and the ring cavity switches into the SA mode-locked mechanism. As shown in the Figures 4(a) and 4(b), keeping other parameters unchanged, uniform mode-locking can also be formed by adjusting $E_{\text{sat}}$. Figures 4(c) and 4(d) are the output temporal profile as well as spectral profile in the 400th round trip, respectively. A uniform mode-locked soliton pulse with 410 fs pulse duration, and 2.3 kW peak power can be achieved. The 3 dB spectral bandwidth is 29.14 nm, thus the TBP is calculated to be 0.458. In addition, Kelly sidebands are so weak that we hardly distinguished them in this mode-locking.

![Figure 4](image-url)

**Figure 4.** Uniform SESAM mode-locked pulse output: evolution of the output pulse (a) and spectrum (b); Output temporal (c) and spectral (d) in the 400th round trip.

**Table 1.** Summary of the parameters for the passively mode-locked Er$^{3+}$-doped fluoride fiber laser.

| Mode-locked mechanism | Pulse width (fs) | 3 dB spectral width (nm) | TBP | Peak power (kW) | Pulse energy (nJ) |
|-----------------------|-----------------|--------------------------|-----|----------------|------------------|
| SESAM                 | 410             | 29.14                    | 0.458 | 2.3           | 0.94             |
| NPR                   | 328             | 34.68                    | 0.436 | 0.61          | 0.202            |
| Hybrid (NPR+SESAM)    | 155             | 79.21                    | 0.467 | 14.78         | 2.29             |

From the simulation results realized by adopting three passively mode-locked mechanisms which are shown in Figures 2 - 4, we summarize the obtained output parameters in Table 1. Obviously, compared to mode-locking only with NPR or SESAM, the hybrid mode-locking yields ultrafast pulse with much higher peak power. Moreover, the pulse width is shorter as well as the spectral bandwidth is broader. In addition, the spectral profile of hybrid mode-locking is more similar to NPR mode-locking than to SESAM mode-locking, indicating the pulse shaping can be realized by NPR component. Besides, it can effectively suppress the number of Kelly sidebands from NPR mode-locking.
In the simulation, we also study the effect of the parameters including gain fiber length, saturable energy of the gain fiber, linear cavity phase delay bias, and small-signal gain on the mode-locked pulse.

We only change the gain fiber length while keeping other parameters unchanged. For the gain fiber with a length of 3 m to 9 m, the erbium-doped fluoride fiber laser can maintain uniform mode-locking. The output pulse properties including the pulse duration, the 3 dB spectral width, the peak power, as well as the pulse energy of the hybrid mode-locking in relation to gain fiber length are shown in Figure 5. By increasing the gain fiber length, the soliton pulse duration reduces, and 3 dB spectral bandwidth increases, as is displayed in Figure 5(a). When the length of the gain fiber increases from 3 m to 9 m, the pulse width decreases from 1.277 ps to 155 fs, as well as the 3 dB spectral width raises from 9.3 nm to 79.2 nm correspondingly, which indicates that within reasonable fiber length, the longer gain fiber could improve gain and provide enough nonlinear phase, thus the pulse width becomes narrower as well as the 3 dB spectral width becomes wider. The relationships between the peak power and pulse energy of the hybrid mode-locked pulse and the gain fiber length are displayed in Figure 5(b). With the gain fiber length increasing from 3 m to 9 m, the peak power raises from 278.03 W to 14.78 kW, as well as pulse energy raises from 0.36 nJ to 2.29 nJ. We would like to mention that when the gain fiber length is beyond 9 m, with the increase of round trip, the pulse will appear periodic intensity fluctuation.

Figure 5. Output features of the hybrid mode-locked fiber laser (a) Relationships of the pulse duration and 3 dB spectral width as well as (b) Peak power and pulse energy with the gain fiber length.

The same method is employed in the research of the effect of $E_{\text{sat}}$ on the hybrid mode-locked pulse laser. The simulation results show that the range of $E_{\text{sat}}$ for obtaining uniform mode-locking is from 500 pJ to 2350 pJ. Figure 6 represents the relationships between the output pulse characteristics and the $E_{\text{sat}}$. From Figure 6(a), with the increase $E_{\text{sat}}$, the pulse duration decreases, and the 3 dB spectral width increases with the $E_{\text{sat}}$. The pulse duration decreases from 2.37 ps at $E_{\text{sat}}=500$ pJ to 155 fs at
The output pulse characteristics versus the small-signal gain are displayed in Figure 8. The simulation results show that uniform mode-locking can be realized when $g_0$ is set as 0.35 m$^{-1}$ to 1.15 m$^{-1}$ and if the $g_0$ is beyond this range, the output pulse will fluctuate in intensity. From Figure 8(a), we can see that with the increase of $g_0$, the pulse duration decreases gradually and then tends to be invariable, while the 3 dB spectral width increases and then becomes invariable. The pulse duration decreases from 1.2 ps at $g_0=0.35$ m$^{-1}$ to 155 fs at $g_0=1.15$ m$^{-1}$. Correspondingly, the 3 dB spectral width raises from 9.85 nm to 79.21 nm. The relationships of the peak power as well as pulse energy between $g_0$ are displayed in Figure 8(b). With $g_0$ increasing from 0.35 m$^{-1}$ to 1.15 m$^{-1}$, the peak power increases from 306.4 W to 14.78 kW, as well as pulse energy raises from 0.37 nJ to 2.29 nJ.
4. Conclusions
In conclusion, a hybrid mode-locked erbium-doped fluoride fiber laser is numerically studied. The simulation results indicate that uniform mode-locked soliton pulse with 155 fs pulse duration, 14.78 kW peak power, as well as 2.29 nJ pulse energy can be realized. By moving the SESAM and NPR components out of the ring cavity sequentially, we demonstrate that the performance of the hybrid mode-locking is much better than that in single SESAM mode-locking and NPR mode-locking. The effect of the parameters including gain fiber length, saturable energy of the gain fiber, linear cavity phase delay bias, and small-signal gain on the hybrid mode-locking is also investigated numerically. In a certain range that supports uniform mode-locked pulse, longer gain fiber length, higher saturable energy of the gain fiber, and larger small-signal gain are beneficial for obtaining higher energy and shorter pulse.

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