Numerical model for nonlinear polarization rotation mode-locked fiber laser

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Abstract: Employing nonlinear Schrodinger equations, a numerical model for nonlinear polarization rotation mode-locked fiber laser was put forward. Jones matrix was used to describe polarization controllers while two-level Giles model was used to calculate the gain. This numerical model has clear physical significance and is conducive to analyze the influence of pump power. With 1.0 m-long erbium doped fiber, 5.8 m-long single mode fiber and 85:15 output coupler, ultrashort pulse with the root-mean-square width of 0.30 ps was derived when pump power was 25 mW. The influence of pump power on the waveform and optical spectrum of mode-locked pulse was investigated, and the relation between pump power and gain distribution in erbium doped fiber was discussed. Mode-locked pulse was derived in experiment, whose optical spectrum was similar with numerical result in shape. The average power of pulse was measured and the variation trend is in line with theoretical result.

Key words: mode-locked; fiber laser; nonlinear polarization rotation; Giles model; gain
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非线性偏振旋转锁模光纤激光器数值模型

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摘 要:利用二能级 Giles 模型来计算掺铒光纤增益,并通过琼斯矩阵描述偏振控制器,提出了一种基于非线性薛定谔方程的非线性偏振旋转锁模光纤激光器的数值模型。该模型具有物理意义更加清晰、便于分析泵浦功率对锁模影响的优点。采用 1.0 m 长的掺铒光纤、5.8 m 长的单模光纤和 85:15 的输出耦合器,当泵浦功率为 25 mW 时数值计算得到均方根宽度为 0.30 ps 的超短脉冲。研究了泵浦功率对锁模脉冲波形和光谱的影响,并讨论了泵浦功率与掺铒光纤中增益分布的关系。通过实验得到了锁模脉冲,其光谱形状与仿真得到的结果相似。测量了不同泵浦功率下脉冲的平均功率,变化趋势也与理论值吻合。

关键词:锁模; 光纤激光器; 非线性偏振旋转; Giles 模型; 增益

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0 Introduction

Nowadays ultrashort pulse generated from passively mode-locked fiber soliton lasers (PMLFLs) has been widely used in domains such as industrial processing, medical application and photonic scientific research due to their special features. So far several schemes have been presented to build PMLFLs, among which nonlinear polarization rotation (NPR)[1-3] technique is known to be cost-effective, compact and easy to realize compared with semiconductor saturable absorption mirror (SESAM)[4-5] or nonlinear optical loop mirror(NOLM)[6]. Moreover, components used in NPR are all-fiber ones, making it compatible to future reconfigurable high-speed optical communication.

There have been several numerical models for NPR. The master equation was presented by Haus et al[7], which describes the stationary state and has nothing to do with the dynamic process of the generation of mode-locked pulse. Another frequently used numerical model refers to the well-known nonlinear Schrodinger equations(NLSE) to describe the transmission of light in fibers. However, the gain of erbium doped fiber amplifier (EDFA) is represented by the following equation[8]:

$$\mathbf{g}=\frac{\mathbf{g}_0}{1+\frac{1}{\mathbf{T_a P_{sat}}}\int |f|^2 dt} \tag{1}$$

where $\mathbf{g}_0$ means the small signal gain coefficiency, $\mathbf{T_a}$ means the photon round time and $\mathbf{P}_{sat}$ is the saturated power. In this case it would be hard to directly reveal the relationship between gain and parameters of experiment setup such as pump power because these parameters are not included in equation (1) and so no idea was obtained about how they influence mode-locked pulse. To solve the problem the rate equations of EDFA is embedded into the NPR numerical model, which helps to calculate the gain coefficient first, and then the generation of ultrashort pulse is simulated. With this numerical model, ultrashort pulse was derived. The influence of pump power on mode-locked pulse and gain in erbium doped fiber was investigated. Mode-locked pulse was derived experimentally, whose optical spectrum and average power were measured and analyzed compared with theoretical result.

1 Modeling of NPR mode-locked laser

Figure 1 shows the setup of an NPR mode-locked fiber laser. The pump, wave-division multiplexing (WDM) coupler and erbium-doped fiber (EDF) together act as an optical amplifier in order to compensate the loss in the cavity, while the polarization dependent isolator (PDI) ensures the unidirectional transmission. It is noted that after passing through PDI, the electric field is linearly polarized. Then the polarization state is adjusted by the polarization controller (PC) to be elliptically polarized, and thus the electric field has two different orthogonal components. Due to the self-phase modulation (SPM) and cross-phase modulation (XPM), these two orthogonal components have different nonlinear phase, and the generation of ultrashort pulse results from their constructive and destructive interference[9]. Point **A** and **B** stand for the beginning and the end of EDF respectively, which will be used in part 2.

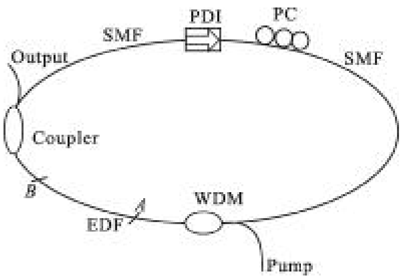

Fig.1 Setup of NPR mode-locked fiber laser

The transmission of light in fiber is described by NLSE, which can be written as[10]:

$$\frac{\partial \mathbf{u}}{\partial \mathbf{z}}=\frac{1}{2}\mathbf{gu}+\left(\frac{\mathbf{g}}{2\Omega_{\mathbf{g}}^2}-\frac{1}{2}i\beta_2\right)\frac{\partial^2\mathbf{u}}{\partial t^2}+ i\gamma\left(|\mathbf{u}|^2+\frac{2}{3}|\mathbf{v}|^2\right)+\frac{1}{3}i\gamma\mathbf{u}^*\mathbf{v}^2 \tag{2}$$

$$\frac{\partial \mathbf{v}}{\partial \mathbf{z}}=\frac{1}{2}\mathbf{gv}+\left(\frac{\mathbf{g}}{2\Omega_{\mathbf{g}}^2}-\frac{1}{2}i\beta_2\right)\frac{\partial^2\mathbf{v}}{\partial t^2}+ i\gamma\left(|\mathbf{v}|^2+\frac{2}{3}|\mathbf{u}|^2\right)+\frac{1}{3}i\gamma\mathbf{v}^*\mathbf{u}^2 \tag{3}$$

where variables **u** and **v** refer to the two orthogonal polarization components. g is the gain of erbium-doped fiber amplifier, β_2 is the group velocity dispersion (GVD) parameter, Ω_g is the gain bandwidth and γ is the nonlinear coefficient. For simplicity here the birefringence of the fiber is ignored.

In order to calculate g, a two-level system approximation is used and the Giles model is expressed by[11]:

$$\frac{d\mathbf{P}_i}{dz}=\left(\mathbf{g}_i\frac{\mathbf{n}_2}{\mathbf{n}_0}-\alpha_i\frac{\mathbf{n}_1}{\mathbf{n}_0}-\gamma_i\right)\mathbf{P}_i,\ i=s,p \tag{4}$$

The subscript s means the signal light while p means the pump light (980 nm). g_i and α_i refer to the emission and absorption coefficient respectively and γ_i, the loss, is assumed 0.2 dB/km for both the pump and signal light. For simplicity only the forward amplified stimulated emission (ASE) noise is considered. The power of signal light P_s is derived by:

$$\mathbf{P}_s=\frac{1}{\mathbf{T}_a}\int(|\mathbf{u}|^2+|\mathbf{v}|^2)dt \tag{5}$$

where T_a is the photon round time. The erbium ion density in upper state(n_2) is derived from:

$$\frac{\mathbf{n}_2}{\mathbf{n}_0}=\frac{\sum_i\frac{\mathbf{P}_i\alpha_i}{h\mathbf{v}_i\zeta}}{1+\sum_i\frac{\mathbf{P}_i(\alpha_i+\mathbf{g}_i^*)}{h\mathbf{v}_i\zeta}} \tag{6}$$

where the total erbium ion density $n_0=8.55\times10^{24}\ m^{-3}$, the effective core area $A_{eff}=6.51\times10^{-12}\ m^2$, the metastable time $\tau=8\times10^{-4}$ s, $\zeta=A_{eff}n_0/\tau$ and v is the frequency of the light. Obviously the erbium ion density in lower state n_1 equals to n_0-n_2 according to the conservation law. In this simulation L1500 EDF (1.0 m, produced by Coractive Company) was used with GVD parameter $D=-21$ ps/(nm*km) and a section of SMF(5.8 m). As P_s is figured out by equation (4) and P_{p0} is given as the initial condition, for a step length dz Runge-Kutta method is used to numerically solve equation(3) and g is determined by $g=10\lg(P_s(z+dz)/P_s(z))/dz$.

PDI and PC are modeled by means of Jones metrics accompanied by the azimuth angles of the wave plates to simulate the rotation of PC, which is demonstrated in [12]. As to the coupler, given the coupling coefficient R we get

$$\begin{bmatrix}\mathbf{u}_{out}\\ \mathbf{v}_{out}\end{bmatrix}=\sqrt{\mathbf{R}}\begin{bmatrix}\mathbf{u}_{in}\\ \mathbf{v}_{in}\end{bmatrix} \tag{7}$$

As the pump is coupled into WDM with connector, 1 dB loss is considered here. Another 1 dB loss is introduced in the cavity for the splicing loss. So far a numerical model for NPR has formed. After one circulation the result is seen as the input of the next circulation and thus the numerical calculation goes on.

2 Simulation results and discussion

2.1 Generation of mode-locked pulse

The original state of u and v was all random noise, pump power was set to be 25 mW and $R=0.15$. If the azimuth angles were tuned properly, steady state was derived and the ultrashort pulse is shown as the solid line in Fig.2(a), with the root-mean-square(RMS) width of 0.30 ps. Solid line in Fig.2(b) depicts the optical spectrum of the pulse, and relative wavelength means the deviation to center wavelength. While Fig.3 is the evolution of the peak power of the pulse in the cavity, which increases rapidly in the first 300 loops and then maintains unchanged.

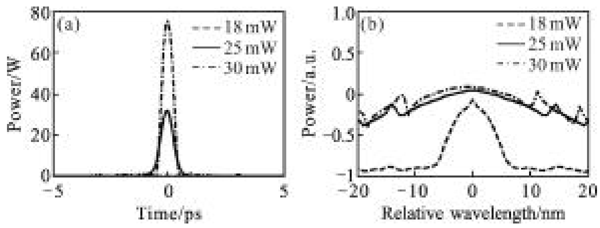

Fig.2 Waveform and optical spectrum of the mode-locked pulse under different pump power

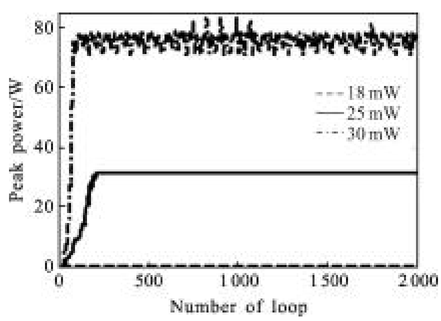

Fig.3 Variation of the peak power with the pulse propagating in the cavity under different pump powers

2.2 Influence of pump power on mode-locked pulse

As explained above, one of the advantages of this numerical model is the convenience to investigate the influence of pump power on ultrashort pulse. When the pump power is lower than 20 mW the gain of EDF is too little to compensate the loss in the cavity so that characters of ultrashort pulse deteriorate, including narrower optical spectrum width and lower intensity in time domain as the dash line in Fig.2. When the pump power is too high, say, 30 mW, there is no obvious change on the RMS width of pulse(dash dot line in Fig.2 (a)), but the optical spectrum sideband is stronger (dash dot line in Fig.2(b)). How the peak power of the pulse varied in the cavity was observed again as the dash dot line in Fig.3. Clearly under such a condition although the peak power is high (dash dot line in Fig.2(a) or Fig.3), it fluctuates with time. In fact when the pump power is higher than 27 mW the nonlinear effect is extremely strong, making the intensity of the pulse unstable.

2.3 Relationship between pump power and gain

The gain of EDF was also investigated when pump power was 18 mW, 25 mW and 30 mW respectively. Fig.4 depicts the variation of the gain in point B with the pulse circulating, and for brevity only the results in first 300 loops are drawn up. The dash line is nearly straight and shows a different character because the pulse power is too little to make the EDF saturated, so a constant gain remains in point **B** in every loop. For the other two cases, compared with Fig.3 when the peak power is low, EDF is unsaturated and has a relatively larger gain. With the peak power increasing rapidly, the gain becomes saturated gradually, reduces to a certain level and finally remains unchanged, which is coincident with equation (1). However, there are also distinctions when the pump power differs. Although the unsaturated gain, which is proportional to the pump power, is larger when pump power is 30 mW, the gain when mode-locked pulse is generated is lower under such a condition because the peak power of the pulse is larger, causing EDF more saturated.

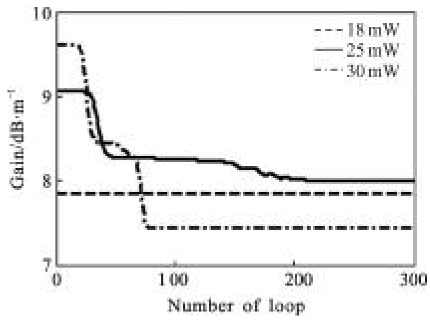

Fig.4 Variation of the gain with the pulse propagating in the cavity under different pump powers

Fig.5 shows distribution of the gain along EDF in the 1 000th loop when pulse is achieved. The **X** axis refers to the length of 1 m EDF from point **A** to **B** in Fig.1. For the three levels of pump power, in the position where pump is added into EDF (that is, point **A** in Fig.1 or the original point of **X** axis in Fig.5), the gain is the largest. With the pulse propagating forward the pump is gradually absorbed and the power decreases, which causes the gain to decrease too.

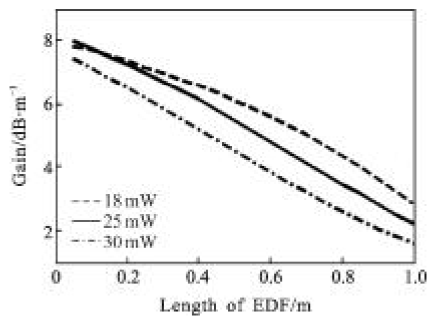

Fig.5 Distribution of the gain along EDF in the 1 000th loop under different pump powers

3 Experiment

According to Fig.1, an NPR mode-locked fiber laser is built with parameters such as the length of SMF and EDF and the split ratio of output coupler in accordance with those used in numerical model. When the pump power was 165 mW, 29.31 MHz ultrashort mode-locked pulse was obtained by tuning PC as in Fig.6, which means the corresponding cavity length is about 6.8 m. The optical spectrum is curved as the solid line in Fig.7. The shape of spectrum is similar to simulated result (dash dot line) and there is also noticeable spectrum sideband.

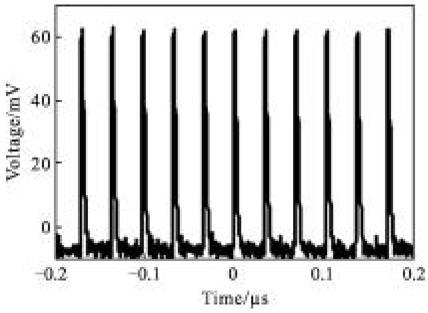

Fig.6 Waveform of mode-locked pulse when pump power is 165 mW

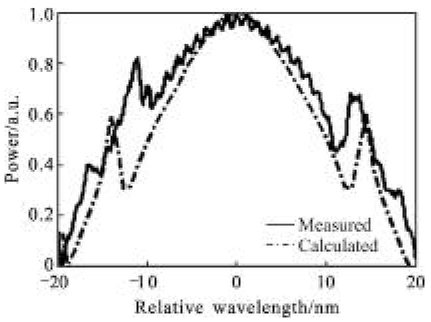

Fig.7 Measured and calculated optical spectrum of mode-locked pulse

Compared with simulated results, the pump power is relatively high to sustain pulse due to coupling loss and splicing loss. When the pump power varied between 130 mW and 195 mW, stable mode-locked pulse was obtained, and the normalized average power of pulse was measured and plotted as the asterisk in Fig.8.

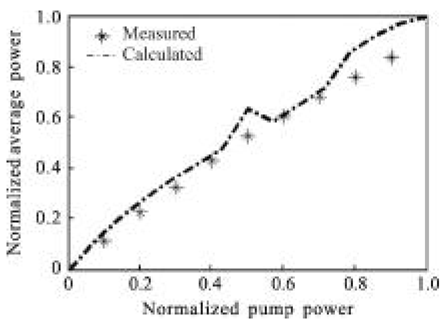

Fig.8 Measured and calculated normalized average output power of pulse under different pump power

Calculated average power by means of numerical simulation with pump power altering from 20 mW to 27 mW is also curved as the dash dot line. Both experimental and theoretical results show the average power increases with the rise of pump power.

4 Conclusion

A novel numerical model for NPR mode-locked fiber lasers is introduced. The Giles model is used to get the gain of EDF, which has the convenience to reveal the relation between the pump power and the state of the mode-locked pulse. Ultrashort pulse with the RMS width of 0.30 ps was derived by ways of numerical simulation. If the pump power is too low or too high, perfect pulse would not form. The variation of the gain with the propagation loops, which decreases when the peak power of the pulse roars at first and remains unchanged when stable pulse is derived, is in line with existing formula. Unsaturated gain when pump power is 30 mW is larger than when pump power is 25 mW, but due to the high peak power of mode-locked pulse the saturated gain is lower. Furthermore, the gain decreases along the EDF because of the consumed pump power. 29.31 MHz ultrashort pulse was derived in experiment, whose optical spectrum is similar with that obtained in numerical simulation. The measured average power of mode-locked pulse also fits well with theoretical results.

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