Energy enhancement in mode-locked fiber lasers by using multiple nonlinear optical fiber loop mirrors

Feng Li (李 锋)* and **P. K. A. Wai (卫炳江)**

Department of Electronic and Information Engineering, Photonics Research Centre, The Hong Kong Polytechnic University, Hung Hom, Hong Kong SAR, China

**Corresponding author: lifeng.hk@gmail.com*

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We propose a method of cascading multiple nonlinear optical loop mirrors (NOLMs) in the laser cavity to enhance the single pulse energy in mode-locked fiber lasers. A geometrical description is used to engineer the transmittance curve of the effective mode locker in the cavity to enlarge the threshold of triggering multi-pulse transition. A full vector model of Ginzburg–Landau equation is adopted to model the pulse evolution in the cavity. Results show that, with the cascading NOLMs configuration, the single pulse energy and peak power can be increased by 170%–188% comparing with that in single NOLM cavity.

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High power mode-locked lasers are very attractive due to the widespread usage in photonics, especially in nonlinear optics such as supercontinuum generation. With the rapid increasing of the applications of supercontinuum outside the optical laboratory, such as optical coherence tomography and optical metrology, where the mobility and reliability are very important, fiber lasers are very desirable to replace the free space Ti:sapphire lasers in such applications. In past decades, mode-locked fiber lasers have been well developed and are the most competitive candidates to replace the free space mode-locked lasers[1]. In mode-locked fiber laser, the light is confined in the fiber core which provides enough nonlinearity to deploy the mode locker based on nonlinear polarization rotation (NPR)[2] or nonlinear optical loop mirror (NOLM)[3–5]. But the high nonlinearity also brings some undesirable phenomena such as multi-pulsing transition into the fiber laser cavity[6–10]. In mode-locked fiber lasers, multi-pulsing transition is the predominant factor limiting the laser output pulse energy. Previously, we have proposed an effective method to enhance the single pulse energy in the fiber laser cavity by cascading multiple NPRs to engineer the transmission curve of the mode locker, which can easily double the single pulse energy and peak power[10,11].

In passively mode-locked fiber lasers, NOLM based on the asymmetric nonlinear phase shifts of the counter-propagating lights can show similar response to NPR[3–5]. In NOLMs, the asymmetry of the counter-propagating lights can be with power or polarization[3–5]. The major drawback of using power asymmetry is that the contrast of the response cannot be very high and power penalty is inevitable. Due to the intrinsic birefringence of the fiber and the NPR of the light while propagating in the fiber, the response of NOLM is very sensitive to the polarization of the input signal[12,13]. Polarization controllers should be used inside and outside the loop to adjust the polarization state in experiments which makes it hard to maintain the stability and repeatability of the output. In 2004, Pottiez *et al.* demonstrated a simple configuration of NOLM with only a quarter-wave plate (QWP) inside a loop of highly twisted fiber[14,15]. This configuration uses a symmetric coupler and the asymmetric is given by the different polarization state of the counter-propagating lights. The advantages of this configuration are not only the simplicity, but also the easily obtained wide tuning range of the working point on the response curve. We investigate the possibility and performance of single pulse energy enhancement in the mode-locked fiber laser cavity by cascading such simple NOLMs.

The schematic of the proposed mode-locked fiber laser with cascading NOLMs is shown in Fig. 1. The linear polarized light will be amplified by the gain fiber and 10% of the light will be coupled out the cavity. The QWP1 after the coupler will convert the light into circular polarization before it is injected into NOLM1. The NOLMs will convert the light into linear polarization and the transmittance will depend on the input power in a periodic response[14,15]. The transmittance of the NOLMs with input light of circular or linear polarization can be approximated as

$$T(P_{in},\alpha)=\frac{1}{2}[1-\cos(2\alpha)\cos(\kappa P_{in}+2\alpha)], \qquad (1)$$

where α is the alignment angle of QWP2, $\kappa=\gamma L/6$, γ is the nonlinear coefficient, and L is the length of the highly twisted fiber in the loop. It is already known that in the laser cavity with such periodic transmittance curve, multi-pulsing transition will definitely be triggered with enough pump power for the gain fiber[10,11]. To be more precise, if the pump power is large enough to push the peak power of the pulse injected into the NOLM to be larger than $(2\pi-2\alpha)/\kappa$, then the transmittance of the pulse can be lower than that of the noise floor which will amplified to trigger the multi-pulsing transition.

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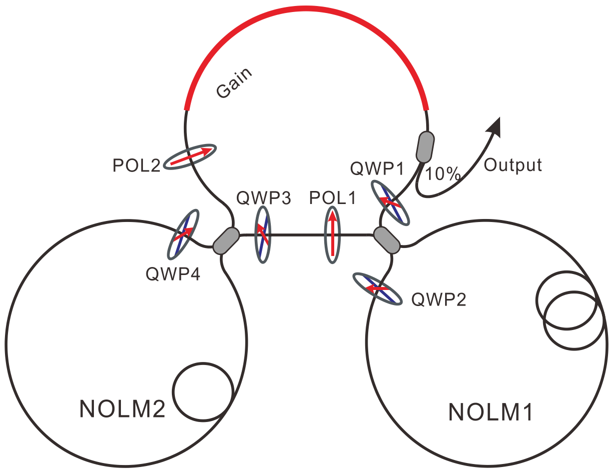

Fig. 1. The schematic of mode-locked fiber laser with cascading NOLMs.

As we have discussed previously, the multi-pulsing transition can be controlled by engineering the response of the laser cavity by cascading nonlinear mode lockers. In our proposed cavity as shown in Fig. 1, while the light passes through NOLM1 and NOLM2 in order, the total transmittance will be

$$T(P_{in}) = T_2(P_{in}T_1(P_{in})). \tag{2}$$

As shown in Fig. 2, the total transmittance is more complex than that of single NOLM. The blue solid curves are the transmittance and the black dash lines are the threshold to trigger multi-pulsing transition. For simplicity, we use the same parameter setting for both NOLMs, where the polarizer angle is $\pi/4$ and the angles of the QWPs are $\alpha_1 = \alpha_3 = 3\pi/4$, $\alpha_2 = \alpha_4 = 0.1\pi$. The fiber lengths of NOLM1 and NOLM2 are both 10 m. The nonlinearity coefficient $\gamma = 1.5$ kW^{-1}m^{-1}.

For single NOLM, the transmittance will drop to below the threshold before the single pulse peak power reach 2.3 kW. By cascading two NOLMs, this limitation is pushed to more than 7 kW. It should be noticed that the transmittance curve of the cascading NOLMs shows more fluctuations than the single NOLM, so complex nonlinear dynamics are expected to be observed in such cavity.

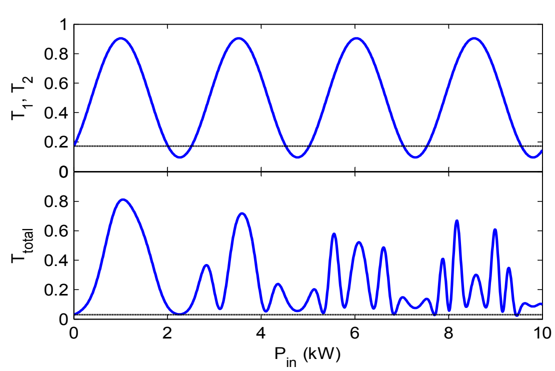

Fig. 2. The transmittance curve of single NOLM and cascaded NOLMs.

To simulate the polarized signal propagation in the laser cavity with highly twisted fiber, the coupled Ginzburg–Landau equations is written as

$$\frac{\partial A_\pm}{\partial z} = \frac{1}{2} g A_\pm + \frac{1}{2}(gT_g^2 - i\beta_2)\frac{\partial^2 A_\pm}{\partial t^2} + i\frac{2\gamma}{3}\left(\left|A_\pm\right|^2 + 2\left|A_\mp\right|^2\right)A_\pm, \tag{3}$$

where $A_\pm$ represents the signal amplitude with right- and left-hand circular polarizations. The fiber dispersion is $\beta_2 = 20$ ps^2/km which is normal dispersion and g is the gain coefficient of the gain fiber with bandwidth $1/T_g$, where $T_g = 0.5$ ps is used. The gain saturation is modeled by

$$g = \frac{g_0}{1 + E/E_{sat}}, \tag{4}$$

where $g_0 = 6.9$ is the small signal gain coefficient, E is the total energy of the signal in the cavity, and E_{sat} is the saturation energy in a cavity round trip which can be varied with the pump power. The gain fiber length is 1 m. The QWPs and POLs are modeled by their Jones matrices under circular polarization description.

We first consider the laser dynamics in the cavity with only NOLM1 to seek for the single pulse energy limitation. By increasing the saturation energy E_{sat} in step size of 0.1 nJ, the stable single pulse solution with maximum single pulse energy after the gain fiber is obtained with $E_{sat} = 1.1$ nJ as shown in Fig. 3. Figure 3(a) shows the pulse evolution along the iterations in the laser cavity in log scale. While a low power sech pulse is used as the seed, the pulse is quickly amplified and reshaped by suppressing the side tails to 50 dB lower than the peak power and approaches the stable solution after 50 round trips. The steady-state pulse is shown in Fig. 3(b). The peak power of the pulse is 2.3 kW which is accordant to the prediction of Fig. 2, and the pulse energy is 3.2 nJ with pulse width 1.2 ps.

While the saturation energy is increased to $E_{sat} = 1.2$ nJ, single pulse solution in the cavity will be unstable. As shown by the evolution in Fig. 4(a), the side tails suppression process before 30 round trips is similar to Fig. 3(a) but the tails are not further suppressed but amplified after 30 round trips and eventually the tails become two new pulses. The stable multi-pulses solution is shown in Fig. 4(b). The total energy of the three identical pulses is 4.4 nJ. The peak power and pulse width are 1.0 kW and 1.3 ps.

In the event that NOLM2 is added into the laser cavity, as predicted with the complex transmittance curve in Fig. 2, the pulse evolution will show more complex nonlinear dynamics. Figure 5 shows the pulse evolutions with different lasing dynamics in the cavity. In Fig. 5, the color map is in linear scale to clearly show the dynamics of the pulses. Figure 5(a) shows the steady-state single pulse evolution with $E_{sat} = 3.8$ nJ.

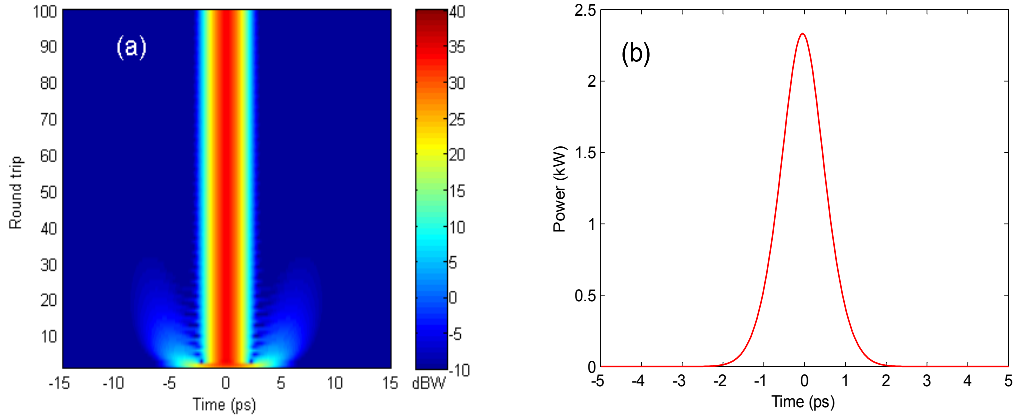

Fig. 3. (a) Pulse evolution and (b) the pulse in the cavity with single NOLM and E_{sat} = 1.1 nJ.

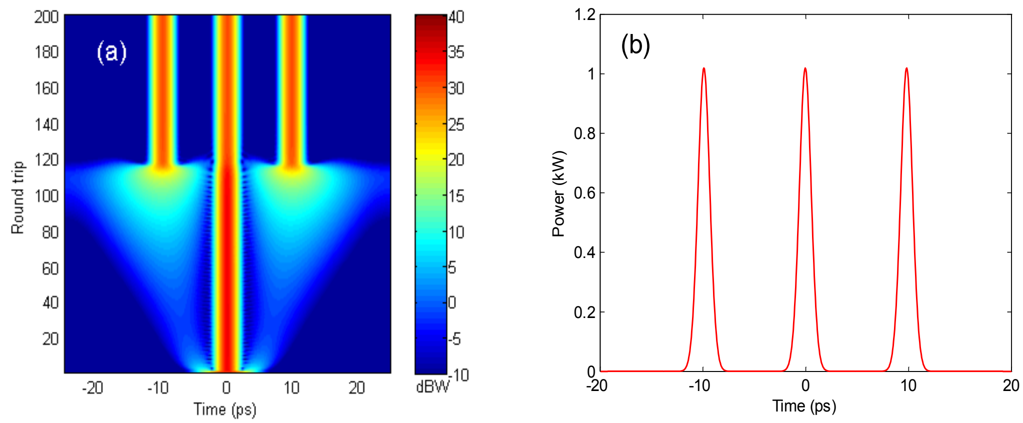

Fig. 4. (a) Pulse evolution and (b) the pulse in the cavity with single NOLM and E_{sat} = 1.2 nJ.

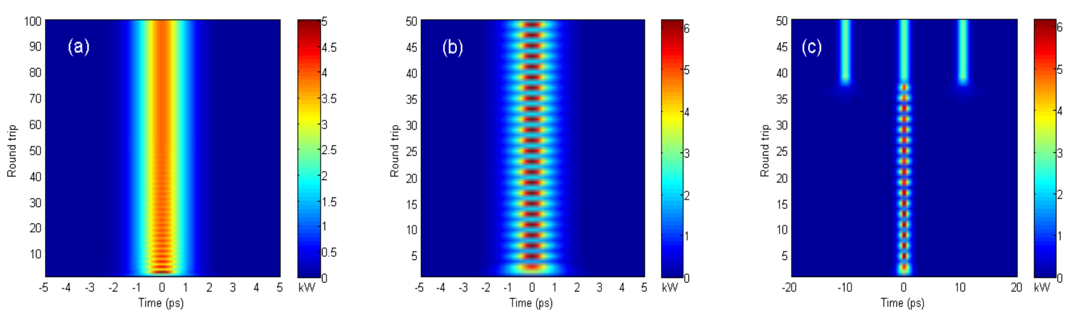

Fig. 5. Pulse evolution in the cavity with cascading NOLMs at saturation energy E_{sat} = (a) 3.8, (b) 5.5, and (c) 5.6 nJ. (a), (b), and (c) show the evolution with steady-state single pulse, periodic single pulse, and multi-pulses solutions in the cavity, respectively.

The pulse waveform in the cavity is shown in Fig. 6(a) with single pulse energy 7.2 nJ, peak power 3.9 kW and pulse width 1.7 ps. Comparing with the solution with E_{sat} = 1.1 nJ in the single NOLM cavity, the single pulse energy and peak power are increased by 125% and 65%.

While E_{sat} increases to more than 3.8 nJ, the pulse in the cavity will not converge to a steady state but will start to oscillate periodically. Figure 5(b) shows the pulse evolution with E_{sat} = 5.5 nJ, where the pulse in the cavity periodically switches between two pulses. The two pulses in the cavity are shown in Fig. 6(b). The small pulse has a peak power 2.1 kW, a single pulse energy 4.6 nJ and a pulse width 2.0 ps. The large pulse has a peak power 6.2 kW, a single pulse energy 9.2 nJ and a pulse width 1.2 ps. Comparing with the single pulse solution in single NOLM cavity, the peak power and single pulse energy are increased

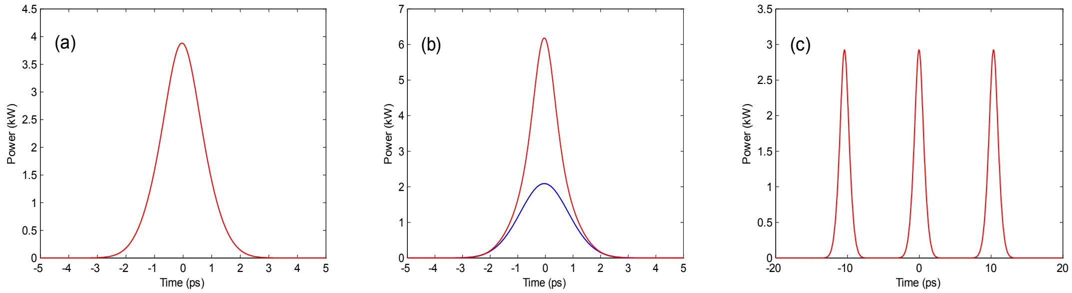

Fig. 6. Pulses in the laser cavity with cascading NOLMs at saturation energy E_{sat} = (a) 3.8, (b) 5.5, and (c) 5.6 nJ. (a), (b), and (c) are the final slices of the evolutions shown in Fig. 5, respectively.

by 170 and 188%. Even with the small pulse in the cavity, the single pulse energy is already increased by 44%.

By increasing E_{sat} to 5.6 nJ, the multi-pulsing transition in the cascading NOLMs cavity is triggered. Before the building up of the multi-pulse solution, the single pulse solution experiences semi-periodic dynamics oscillation. Eventually, three identical pulses appear in the cavity and become the stable multi-pulse solution. The pulses have a peak power 2.9 kW, a pulse width 1.5 ps, and a total pulse energy of 14.6 nJ. Actually, if the saturation energy E_{sat} is further increased to higher value, more complex nonlinear dynamics can be observed before the building up of the multi-pulse solution but it is not the focus of this paper.

In conclusion, a method of cascading multiple NOLMs in the laser cavity is proposed to enhance the single pulse energy in mode-locked fiber lasers. Geometrical description predicts that the peak power can be greatly enhanced by adding the second NOLM. Simulations with a full vector model show that, with the cascading NOLMs configuration, single pulse energy and peak power can be increased by 125% and 65% with steady-state single pulse output. At periodic oscillating state, the single pulse energy and peak power of the laser output can even be enhanced 170% and 188% which are almost triple the values of the pulse in single NOLM cavity.

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