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L. M. Zhao, D. Y. Tang, T. H. Cheng, and C. Lu

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Ultrashort pulse generation in lasers by nonlinear pulse amplification and compression

L. M. Zhao,[a)] D. Y. Tang, and T. H. Cheng
School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

C. Lu
Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hong Kong, People's Republic of China

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Generation of ultrashort, transform-limited pulses in a laser resonator by means of nonlinear pulse amplification and compression is observed both numerically and experimentally; this constitutes another type of pulse shaping mechanism in the mode-locked lasers. It is shown that as a result of nonlinear pulse compression, mode-locked pulse with pulse width beyond the gain bandwidth limitation could be directly generated in a laser. © *2007 American Institute of Physics*.
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Ultrashort pulse generation in lasers is a topic that has been extensively studied. Mode locking has been the standard technique of achieving short pulses from a laser. It relies on the coherent superposition of oscillating longitudinal modes. In a practical laser system due to the effects of cavity dispersion, mode-locker response time limitation, etc., generally not all modes can be phase locked. Therefore, the formed pulses are broader than that limited by the gain bandwidth. Through incorporating nonlinear pulse propagation effects, such as the self-phase modulation (SPM), into the mode-locking process, it was shown that optical solitons could be formed in lasers with net negative cavity group velocity dispersion (GVD), and soliton effect can lead to significant mode-locked pulse narrowing.[1,2] So far, soliton operation of lasers has been widely used to achieve ultrashort pulses from lasers.

However, for the mode-locked fiber lasers, soliton operation has a serious drawback. The mode-locked pulses can only have low peak power due to the large inherent fiber nonlinearity and long fiber cavity. Furthermore, the pulse width is limited in the hundreds of femtosecond level. Increasing pump strength of the lasers can only increase the number of pulses rather than their peak power. To increase the mode-locked pulse energy and peak power, Tamura *et al.* used an approach of so-called stretched-pulse mode locking.[3,4] Pulses with significantly larger energy were obtained, however, in cost of increased pulse width. Recently, Ilday *et al.* have also proposed a wave-breaking-free technique for achieving large energy pulses.[5] The basic idea of the technique is to possibly reduce the effects of fiber nonlinearity so to minimize the influence of cavity effect on the mode-locked pulses. In addition, through using a dispersive delay line in cavity to provide anomalous GVD with negligible nonlinearity, the self-similar pulse evolution was also demonstrated in a mode-locked Yb-fiber laser.[6] Lasers operating in the state can generate large pulse energy with linear frequency chirp, which can be externally dechirped to obtain the transform-limited pulse.[7] Nevertheless, the technique is only feasible for lasers with gain media of broad gain bandwidth and large saturation intensity. In this letter we report on another state of mode-locked laser operation. We show both numerically and experimentally that through appropriately designing laser cavity, one can take advantage of the large nonlinearity of optical fibers to generate large energy transform-limited pulses with spectral bandwidth broader than the laser gain bandwidth directly from a laser oscillator. Stable mode-locked pulses with pulse width of about 56 fs have been obtained from an erbium-doped fiber laser.

The pulse dynamics in a femtosecond laser is determined by the interplay between the overall cavity dispersion and nonlinearity, gain and losses, as well as the detailed pulse evolution in the cavity and the cavity boundary condition. In order to obtain a desired mode-locked pulse from the lasers one should carefully balance the interaction among the effects. Previous studies have shown that a nonlinear pulse compression process can generate supernarrow pulses.[8] Pulse amplification in gain media with normal dispersion can also achieve large energy pulse without pulse splitting.[9] If these two processes could be combined in the pulse shaping process of a mode-locked laser, it would be expected that significantly large energy narrow mode-locked pulses could be formed. Certainly, it should also bear in mind that different from the pulse propagation processes, any mode-locked state must also satisfy the laser cavity boundary condition.

We numerically investigated the feasibility of forming such a mode-locking state in lasers. It turns out that through appropriately designing laser cavity so that both the cavity dispersion and nonlinearity are managed, a mode-locked fiber laser will automatically operate in the state. We used a fiber laser as illustrated in Fig. 1 for the calculation. The fiber laser cavity is a unidirectional ring comprising a segment of erbium-doped fiber (EDF) with normal GVD, two segments of the standard single mode fiber (SMF). The laser is mode locked with the nonlinear polarization rotation (NPR) technique, and its output coupler is set at the position of the intracavity polarizer. We used a model as described in Ref. 10 to simulate the laser operation. Different from the conventional models, which simply assume that the pulse shaping within one cavity roundtrip is small and ignores all effects associated with the pulse circulation in the cavity,

[a)]Electronic mail: luming_zhao@pmail.ntu.edu.sg

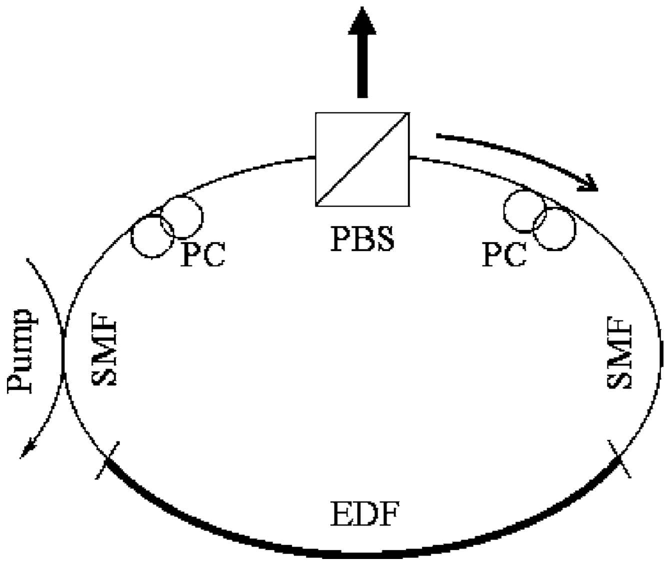

FIG. 1. Schematic setup used for direct generation of transform-limited pulses (PBS, polarization-dependent beam splitter; PC: polarization controller; SMF, standard single-mode fiber; EDF, erbium-doped fiber).

we have explicitly taken into account actions of every cavity component and the cavity boundary condition on the formed pulse.[10] We have used the following parameters in the simulations: $\gamma=3\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$, $k''_{\mathrm{EDF}}=4.08\times10^{-2}\ \mathrm{ps}^2/\mathrm{m}$, $k''_{\mathrm{SMF}}=-2.55\times10^{-2}\ \mathrm{ps}^2/\mathrm{m}$, $k'''=-1.27\times10^{-4}\ \mathrm{ps}^3/\mathrm{m}$, $\Omega_g=24$ nm, gain saturation energy $E_{\mathrm{sat}}=300$ pJ, cavity length $L=2.4_{\mathrm{SMF}}+2.1_{\mathrm{EDF}}+0.6_{\mathrm{SMF}}=5.1$ m, fiber beat length $L_b=L/2$, and the orientation of the intracavity polarizer to the fiber fast birefringent axis $\Psi=0.152\pi$. The net cavity GVD is about $9.18\times10^{-3}\ \mathrm{ps}^2$.

The laser has a typical dispersion managed (or stretched-pulse laser) cavity. It was found that the detailed features of its mode-locked operation sensitively depend on the selection of the SMF length and the output coupling strength. Generally either the multiple pulses with low peak power or broad pulse with large pulse energy were obtained, which corresponds exactly to the operations of the stretched-pulse lasers. These mode-locked operations of the laser can be well explained based on the cavity peak clamp effect and the accumulated nonlinear phase shift of the mode-locked pulse in one cavity transit.[10] However, through appropriately selecting the cavity output position and strength, which services as an effective way to manage the local pulse intensity in the cavity, a mode-locked state as shown in Fig. 2 could be obtained. Compared, with the other mode-locked states obtained in the laser, it has not only large pulse energy but also narrow pulse width and a spectral bandwidth that is far broader than the laser gain bandwidth. For the case shown, the mode-locked pulse has a peak power of nearly 5 kW, pulse width of about 53.4 fs, and 3 dB bandwidth of 75.6 nm.

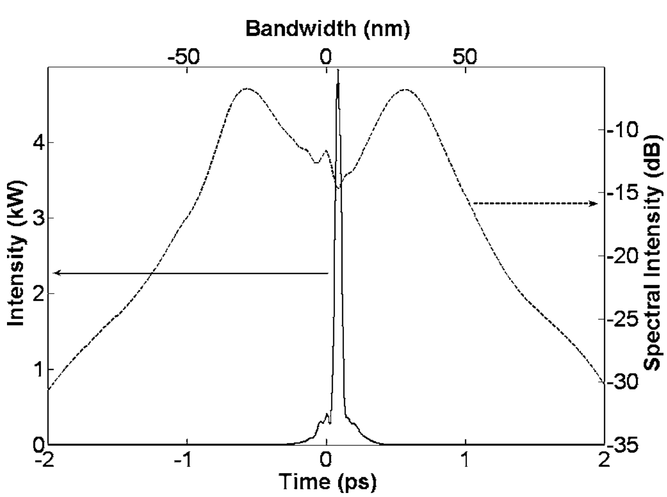

FIG. 2. Numerically calculated laser output pulse.

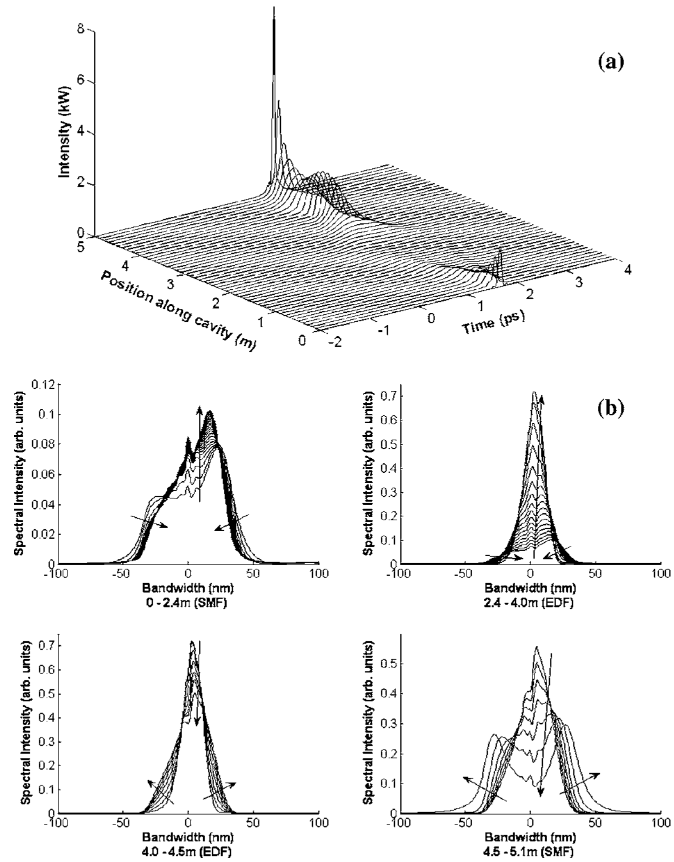

FIG. 3. Pulse shaping within one cavity transit. (a) Temporal evolution, (b) Spectral evolution. The arrows indicate the direction of the spectrum evolution as the pulse propagates in the fibers.

To understand the formation of the pulse, we show in Fig. 3 the corresponding temporal and spectral evolution in one cavity transit. The round trip begins from the polarization dependent beam splitter (PBS) and along the arrow direction, as shown in Fig. 1. It reveals that the pulse is actually formed as a result of the nonlinear pulse amplification and compression in the cavity, which constitutes therefore another type of pulse shaping mechanism in the mode-locked lasers. With appropriate selection of the laser output position and strength, combined with the cavity dispersion management, the peak power of the mode-locked pulse in cavity becomes so controlled that strong pulse intensity only occurs in a short segment of the cavity. Therefore, the accumulated nonlinear phase shift of the pulse within one cavity transit still remains small, which effectively suppresses the multiple pulse formation effect of the lasers. Under strong pumping and single pulse in cavity, the mode-locked pulse is nonlinearly amplified in the gain fiber. This is characterized by the pulse spectral narrowing in the initial stage of the amplification, which is caused by the gain bandwidth limitation, and

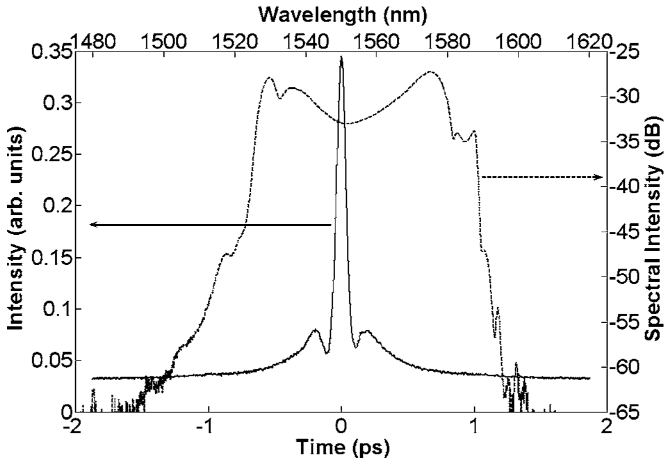

FIG. 4. Experimental autocorrelation trace and optical spectrum.

the pulse spectral broadening in the final stage of the amplification caused by the SPM, cross-phase modulation, and four-wave-mixing between the two orthogonal polarization components. When the pulse subsequently propagates in the SMF, it is then nonlinearly compressed, characterized by the further pulse spectral broadening. Eventually the pulse spectrum becomes superbroad. At the position of the laser output (the end of the round trip), the pulse becomes a near transform-limited pulse with ultranarrow pulse width and high peak power. We emphasize the natural formation of the nonlinear pulse amplification and compression in the mode-locking state, which is fundamentally different from the pulse shaping process in the stretched-pulse lasers, where the mode-locked pulse has everywhere only weak nonlinearity. It is the nonlinear pulse amplification that generates a very large energy pulse, which through nonlinear compression becomes very high peak power and spectral width broader than the gain bandwidth.

Guided by the numerical simulations we have also experimentally realized the mode-locked laser operation in an erbium-doped fiber laser. The fiber laser has a cavity configuration exactly as shown in Fig. 1. The EDF used has a length of 210 cm and erbium doping concentration of 2880 ppm. Its GVD parameter is about -32 (ps/nm)/km. The segment of SMF used to nonlinearly compress the pulse is 62 cm. The length is experimentally optimized so that a near transform-limited pulse is directly emitted from the laser under the maximum available pump power of the laser. The length of another segment of SMF used is 2.4 m, which is incorporated in the cavity to manage the dispersion of the cavity so that the net cavity dispersion is positive and near zero. We estimate that the cavity dispersion is about $0.003-0.018$ ps^2. A polarization dependent beam splitter is used both as the intracavity polarizer for the NPR mode locking and as cavity output coupler. It has the advantage of outputting only the rejected polarization of the NPR mode locking, and the output coupling strength increases with the peak power of the mode-locked pulse.

Figure 4 shows the optical spectrum and autocorrelation trace of the mode-locked state obtained. The mode-locked pulse has a pulse width of about 56 fs (full width at half maximum) if a hyperbolic secant profile is assumed, and 3 dB bandwidth of about 53 nm. The time-bandwidth product is 0.37, slightly larger than that of the transform-limited pulse. In the state the average output power of the laser is 64.9 mW, under pump strength of 700 mW. As the repetition rate of the laser is 38.5 MHz, it gives the single pulse energy of about 1.69 nJ. We note the existence of small pedestals in the measured autocorrelation trace, which is a characteristic of the pulses formed in the mode-locking state. As can be seen from the numerically calculated pulse profile, there is also an asymmetrical pulse wing associating with the main pulse. Numerically we found that the formation of the small pulse wing is a result of pulse breaking in the laser. The experimental results are in good agreement with the numerical simulations.

In conclusion, we have reported observation of a self-organized mode-locking state of lasers formed under strong cavity nonlinearity and appropriate design of the cavity. The state involves the nonlinear pulse amplification and compression in the pulse shaping process in the cavity, and as a result of the pulse shaping mechanism high peak power ultrashort transform-limited pulse could be directly generated from the lasers. Under operation of the state an erbium-doped fiber laser has emitted stable mode-locked pulses with 1.69 nJ single pulse energy, about 56 fs pulse width. We believe such a mode-locked pulse shaping mechanism could be a useful ultrashort pulse laser technique and it can also be implemented in other types of lasers.

[1]J. D. Kafka and T. Baer, Opt. Lett. **14**, 1269 (1989).
[2]M. E. Fermann, M. J. Andrejco, M. L. Stock, Y. Siberberg, and A. M. Weiner, Appl. Phys. Lett. **62**, 910 (1993).
[3]K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, Opt. Lett. **18**, 1080 (1993).
[4]K. Tamura, L. E. Nelson, H. A. Haus, and E. P. Ippen, Appl. Phys. Lett. **64**, 149 (1994).
[5]F. Ő. Ilday, J. R. Buckley, H. Lim, F. W. Wise, and W. G. Clark, Opt. Lett. **28**, 1365 (2003).
[6]F. Ő. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, Phys. Rev. Lett. **92**, 213902 (2004).
[7]J. R. Buckley, S. W. Clark, and F. W. Wise, Opt. Lett. **31**, 1340 (2006).
[8]Nail N. Akhmediev and Nina V. Mitzkevich, IEEE J. Quantum Electron. **27**, 849 (1991).
[9]M. E. Fermann, V. I. Kruglov, B. C. Thomsen, J. M. Dudley, and J. D. Harvey, Phys. Rev. Lett. **84**, 6010 (2000).
[10]D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, Phys. Rev. A **72**, 043816 (2005).