Numerical study on a frequency-tunable actively mode-locked fiber laser*

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We have numerically presented an actively mode-locked fiber laser with tunable repetition rate based on phase modulator. By finely optimizing intra-cavity parameters, the ultrashort pulses with tunable repetitive frequency at giga hertz level can be easily generated due to the balance between dispersion and nonlinearity in the fiber laser cavity. When the pulse frequency is changed from 1.0 GHz to 4.2 GHz, the spectral width increases from ~15.65 nm to ~27.25 nm. In addition, the corresponding pulse duration decreases from ~81.59 ps to ~31.57 ps. Moreover, these output pulses with giga hertz repetitive rates and the picosecond widths can be further compressed by using the reasonable dispersion medium. For the pulse regime with repetition frequency at giga hertz level, the obtained smallest pulse duration is about ~62 fs based on chirp pulse compression. We hope that these simulation results can promote further research and application in the ultrashort pulse lasers with high repetition rate.

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In recent decades, pulse fiber lasers with high repetition frequency have attracted much attention due to their widespread applications in optical frequency comb[1,2], optical communication[3,4], optical measurement[5], nonlinear frequency conversion[6], wideband signal processing[7] and material machining[8]. As the most typical ultrafast light source, mode-locked fiber lasers have generally the fundamental repetition frequency below 1 GHz, which is mainly limited by the cavity length of the fiber laser[9]. In addition, there is the attractive method to achieve the high-repetition-rate pulses in the passive mode-locked fiber lasers with a fixed cavity length by greatly increasing the pump power. Under the high pump power, the fiber laser can easily generate multiple pulses due to energy quantization[10]. Then, the interactions among them make the fiber laser form different pulse states. In certain condition, the fiber laser can switch to a state with a regular pulse interval, which is also called as the harmonic mode locking (HML)[11,12]. This regime can operate at many times of the corresponding fundamental rate. However, the harmonic mode-locked fiber lasers have disadvantages of weak stability, poor handle ability and high randomicity. Therefore, the alternative way is to explore the high-repetition-frequency pulses in the actively mode-locked fiber lasers[13-16].

Specially, actively mode locked fiber laser has the typical advantages of high repetition rate, good controllability flexible structure, tunable wavelength and frequency, which can make it become an excellent optical source in the optical fiber system[17]. One of the most important components for the actively mode-locked fiber laser is the modulator. When the corresponding modulation frequency is an integral multiple of the fundamental frequency determined by the length of the fiber cavity, the mode-locked pulse is generated and enhanced in the cavity, finally resulting in the formation of the stable ultrashort pulses with high repetition rate. Apart from the high repetitive frequency, there is an increased demand for the pulse width at a specific repetition in some application fields. Due to the balance of dispersion and nonlinearity in the cavity, it is very different to obtain the output pulses with femtosecond duration in the actively mode-locked fiber laser with net-normal dispersion[18]. The output pulses are generally compressed by external cavity compression method based on the dispersion compensation technique[19]. Dissipative soliton pulse with the pulse duration of ~10 ps at 44.1 MHz in the actively mode-locked fiber laser has been reported[13]. By the extra-cavity compression, the obtained smallest pulse width is 560 fs. Recently, YAO et al[16] obtained the output pulses with the pulse width of ~4 ps and the repetition rate of ~4 GHz in the actively mode-locked fiber laser. Therefore, it is necessary to explore narrower pulses with femtosecond level in the actively mode-locked fiber lasers.

In this paper, the actively mode-locked fiber with tunable

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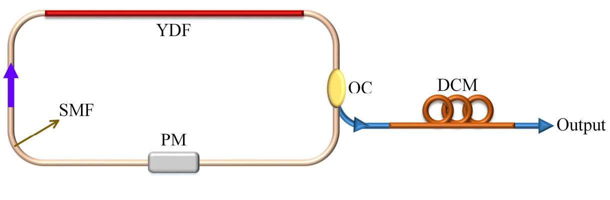
repetitive frequency and ultrashort pulses at giga hertz order is demonstrated. The mode-locked pulses with repetition rate at several giga hertz ranges can be obtained by appropriately optimizing the cavity structure. Besides, at proper parameters, the optical spectrum width changes from ~15.65 nm to ~27.25 nm with the increase of repetition frequency from 1.0 GHz to 4.2 GHz and the pulse duration changes from ~81.59 ps to ~31.57 ps. Further, the output ultrashort pulses with ~31.57 ps at 4.2 GHz can be compressed to ~62 fs based on the dispersion compensation method. As far as we know, the pulse regime with the pulse width of ~62 fs and the repetition rate of 4.2 GHz is reported for the first time at the actively mode-locked fiber lasers.

The structure of the actively mode-locked fiber laser considered in theoretical modeling system is illustrated in Fig.1. The fiber laser is mainly composed of Yb-doped fiber (YDF), optical coupler (OC), phase modulator (PM), single-mode fiber (SMF) and dispersion compensation medium (DCM). Here, the YDF is the gain fiber for producing the laser emission at 1 060 nm wavelength range. Apart from the gain fiber, other fibers are the SMFs. The output ratio of OC can be changed according to the requirements. The DCM is used for external cavity compression. In addition, as the important one of these components, the PM is used for achieving pulse amplitude modulation. In point of fact, the PM can act as the mode-locked device and play the important role in the generation of ultrashort pulses for the fiber laser. The mode-locked pulses with different repetition rates and pulse durations are obtained by properly adjusting corresponding parameter, such as modulation frequency and phase modulation depth. These components constitute the loop laser cavity. Finally, the intra-cavity pulses transmit clockwise around the loop and output laser by means of the OC component.



YDF: Yb-doped fiber; OC: optical coupler; PM: phase modulator; SMF: single-mode fiber; DCM: dispersion compensation medium

Fig.1 Schematic diagram of the laser setup

In the theoretical modeling, the components of the fiber laser cavity have different parameter values, which are described as follows. The nonlinear propagation of light waves through the SMF and YDF areas in the ring can be modeled by the nonlinear Schrodinger equation[18] and its expression is given by

$$\frac{\partial A}{\partial z}=-\frac{\mathrm{i}\beta_2}{2}\frac{\partial^2 A}{\partial T^2}+\mathrm{i}\gamma|A|^2A+\frac{g-\alpha}{2}A+\frac{g}{2\Omega_{\mathrm{g}}^2}\frac{\partial^2 A}{\partial T^2}, \quad (1)$$

where A is the pulse amplitude, z is the distance of transmission fiber, β_2 is the group velocity second-order dispersion parameter of the fiber, including YDF and SMF, γ represents the corresponding nonlinear coefficient, α represents the loss parameter, g refers to the saturation gain coefficient, and Ω_{g} represents the gain bandwidth. Among them, the gain coefficient is related to the characteristics of the gain fiber itself and the energy of the incident optical pulse. Besides, their relation expression is as follows

$$g=\frac{g_0}{1+\int|A|^2\,\mathrm{d}t/E_{\mathrm{sat}}}, \quad (2)$$

where g_0 represents the small-signal gain and E_{sat} is gain saturation energy. It should be noted that the g_0 of YDF is only considered and the g_0 of SMF can be negligent.

Here, the optimized modelling parameters are as follows[13]. For YDF, it has the length of ~1.6 m. The corresponding group velocity dispersion (β_2), nonlinear coefficient (γ), small-signal gain (g_0), gain bandwidth (Ω_{g}) and gain saturation energy are ~23 ps^2/km, ~5 W^{-1}/km, 2 m^{-1}, 40 nm and 50 W, respectively. In addition, the SMF is divided into two parts, SMF1 and SMF2. The total length is 8.4 m. The corresponding β_2 is ~28.6 ps^2/km. Thus, the cavity length is about 10 m and the calculated fundamental frequency is ~20 MHz. For OC, the 10% port is used as the laser output. For PM, the amplitude modulation depth is set to 1%. Moreover, the modulation frequency can be tuned from 1.0 GHz to 4.2 GHz. If the repetition rate exceeds the ranges, the output pulses would be unstable. After that, a split-step Fourier method is used for solving the nonlinear propagation model and the corresponding mode-locked pulse operation can be achieved based on MATLAB software by finely changing the intra-cavity parameters.

In order to observe the mode-locked pulses with high repetition rate, the modulation frequency of PM is first set to 1.0 GHz and the other parameters keep unchanged. Then, the optical spectrum and pulse trains can be described, as shown in Fig.2(a) and (b). Obviously, it can be seen from the figure that the optical spectrum in the range from 1 020 nm to 1 100 nm is smooth and wide. Besides, the center wavelength of optical spectrum is 1 060 nm and the corresponding spectral width (full width at half maximum, *FWHM*) is about 15.65 nm. In addition, as shown Fig.2(b), the pulse shape has a Gaussian profile. The pulse width (*FWHM*) is approximately 81.59 ps, which is similar to the observation in Ref.[20]. The calculated time bandwidth product (TBP) is ~341, indicating that these pulses are strongly chirped, which results from the large dispersion in the ring cavity with net-normal dispersion[18,21,22]. Then the modulation frequency is gradually increased. Fig.2(c) and (d) illustrate the optical spectrum and pulse trains at 3 GHz repetition rate. Clearly, the optical spectrum with a 3 dB width of ~24.46 nm becomes broader and the pulse duration with an *FWHM* of ~40.58 ps gets narrower.

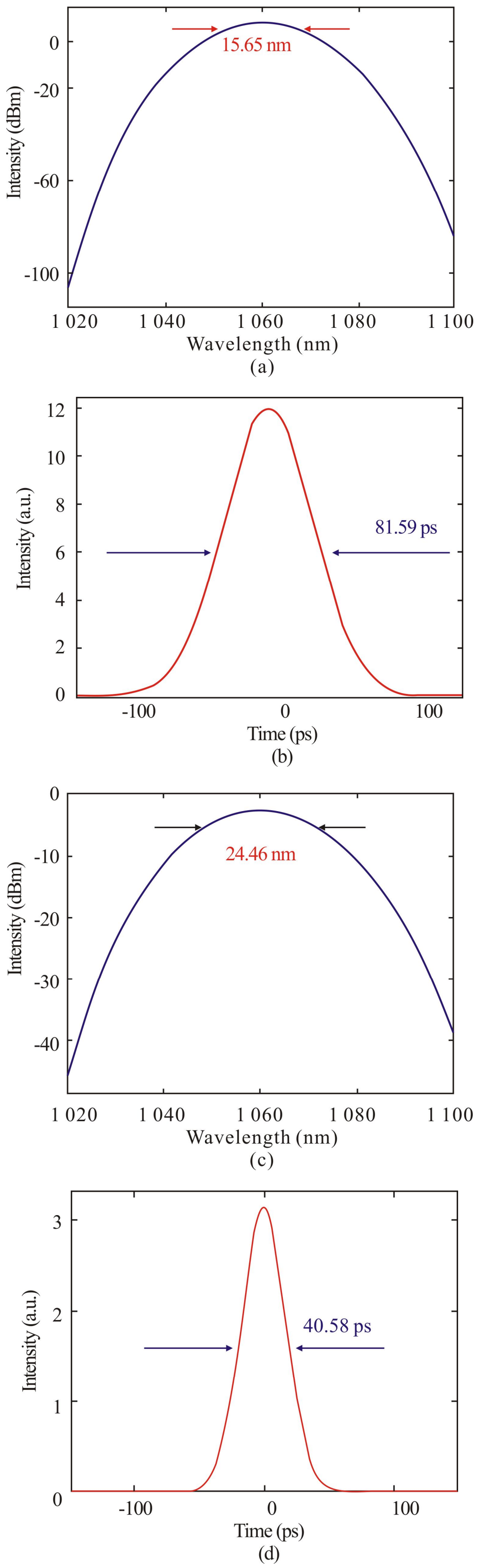


Fig.2 (a) Optical spectrum and (b) temporal train of output pulse with 1 GHz repetition rate; (c) Optical spectrum and (d) temporal train of output pulse with 3 GHz repetition rate

Furthermore, the spectral width and pulse width of the output pulses at different repetition rates are estimated, which has been summarized in Fig.3. As can be seen, with the increment of repetitive frequency, the pulse width decreases stage by stage, while the spectral width increases step by step, which accords with the fundamental law in ultrafast optics. Moreover, the pulse width reduces from ~81.59 ps to ~31.57 ps and spectral width increases from ~15.65 nm to ~27.25 nm as the repetition frequency continues to improve from 1.0 GHz to 4.2 GHz. When the repetition rate increases continuously, the optical spectrum of output pulses is out of shape and pulse energy also makes considerable reduction. Therefore, the repetition frequency cannot be more than the boundary value.

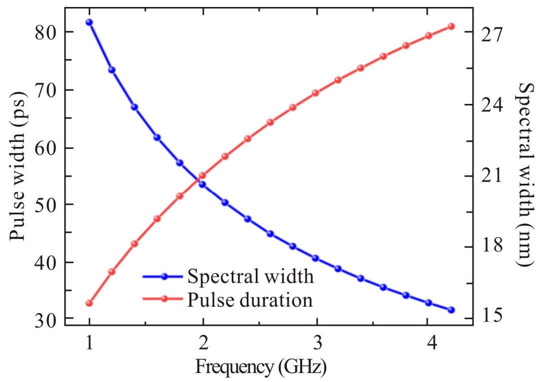


Fig.3 Pulse width and spectral width as a function of repetition frequency

In the above stimulation, the obtained narrowest pulse width and spectral width are 31.57 ps and 27.25 nm. The corresponding TBP exceeds 200 due to the existence of large chirp. Thus, it is necessary to compress these pulses by using dispersion compensation. The proper dispersion medium is chosen and the corresponding dispersion parameter is about −46.3 ps^2/km. By further optimizing the length, the chirped pulses are compressed to the maximum extent. Herein, the input average powers of these pulses are equal. Fig.4 shows the theoretical calculation results. The compressed pulse widths at 2 GHz with different lengths are presented in Fig.4(a) and (b). The optimal length is ~32.56 m and the corresponding pulse width is ~80.6 fs. Fig.4(a) and (b) display the compressed pulse widths at 4 GHz with the changed lengths. The proper length is ~15.73 m and the smallest pulse width is ~63.1 fs. Further, the compressed pulse widths with the optimal length at different repetition rates are summarized, as demonstrated in Fig.5. It can be seen that the optimal length and pulse width gradually decrease as the repetition frequency increases. At the maximum frequency, the length and width are ~14.92 m and ~62 fs, respectively. These results suggest that it can be possible to achieve the ultrashort pulses below 100 fs in the actively mode-locked fiber lasers.

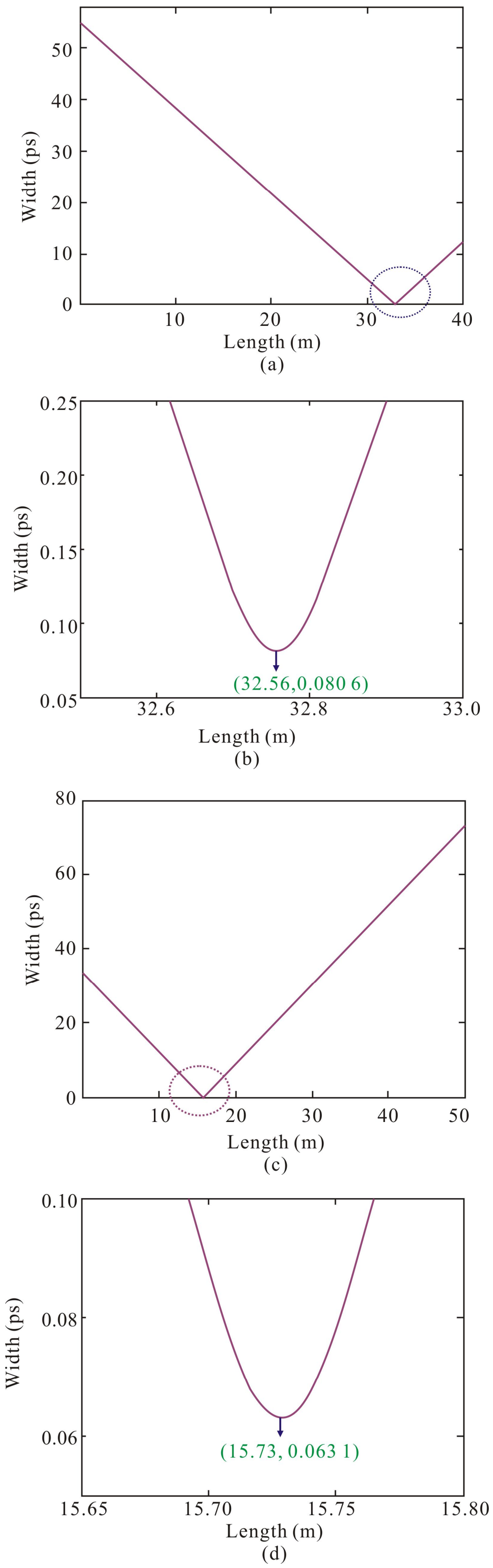


Fig.4 (a) Pulse width after external compression and (b) the corresponding close-ups of blue dashed area at 2 GHz repetition rate; (c) Pulse width after external compression and (d) the corresponding close-ups of blue dashed area at 4 GHz repetition rate

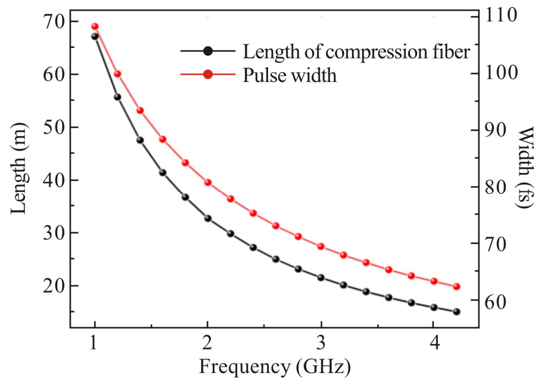


Fig.5 Length of compression fiber and pulse width after external compression as a function of repetition frequency

In conclusion, the pulse dynamics of an actively mode-locked fiber at high repetitive rate has been investigated in theory. By appropriately setting the parameters of the laser cavity, the ultrashort pulses at giga hertz repetitive frequency level with tunable characteristics can be achieved. Especially, when the optimized parameters are defined and the repetition frequency of output pulses tunes from 1.0 GHz to 4.2 GHz, the pulse width decreases from ~81.59 ps to ~31.57 ps. At the same time, the optical spectrum increases from ~15.65 nm to ~27.25 nm. Besides, the external cavity compression is conducted by using the dispersion compensation method. Based on the proper dispersion medium with anomalous dispersion, the pulses with dozens of picoseconds can be de-chirped to below ~110 fs. The obtained narrowest pulse width is about ~62 fs at the repetition rate of 4.2 GHz. These theoretical results will be helpful to design and optimize the ultrafast fiber lasers with high repetition frequency.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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