A theoretical and experimental study on all-normal-dispersion Yb-doped mode-locked fiber lasers

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We report on a theoretical and experimental study of an all-normal-dispersion (ANDi) Yb-doped mode-locked fiber laser, in which nonlinear polarization rotation (NPR) is used to realize mode-locking without any dispersion compensation. Based on the coupled nonlinear Schrödinger (CNLS) equation, a model simulating the mode-locked process of an all-normal-dispersion ring fiber laser is developed, which shows that the achievement of stable mode-locking depends on the alignment of the polarization controller (PC) along the fast-polarization axis of the fiber, the birefringence intensity, and the net cavity dispersion. According to the theoretical analysis, stable mode-locked pulses with pulse duration 300 ps and average output power 33.9 mW at repetition rate 36 MHz are obtained.

Keywords: all-normal-dispersion, nonlinear polarization rotation, mode-locked, Yb-doped fiber laser

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1. Introduction

As an emerging technology in the laser field, the mode-locked fiber laser has great development potential; especially, all-normal-dispersion (ANDi) mode-locking fiber lasers with simple structure, small volume, high output power, and mode-locking stability have become a noticeable field. Without introducing any dispersion compensation device into the cavity, a highly chirped pulse with wide pulsed width (∼100 ps) can be obtained from an oscillator. And a wide pulse width can reduce the peak power of the pulse in the optical resonant cavity, which enables the carrying of higher light pulse energy without accumulation of excessive nonlinear effects on the stability of mode-locking.[1] Usually, the main idea of traditional fiber chirped pulse amplification (CPA) is to stretch an ultrashort seed pulse to reduce peak power and then amplify it, which can avoid gain saturation and nonlinear effects caused by high peak power.[2,3] Since ANDi mode-locking fiber has the characteristics of high energy, wide pulse duration, and low peak power, this kind of laser can be amplified to high output power directly and leave out pulsed stretched segment for the CPA system. So it is necessary for us to study the ANDi mode-locking fiber laser in depth. As is well known, some results about ANDi erbium-doped fiber laser has been reported recently. In 2000, Kim *et al.*[4] performed a theoretical analysis and simulation on the ANDi erbium-doped fiber laser. They established a pulse dynamics model and pointed out that the pulse of the periodic disturbance depended on the strength of the fiber birefringence and the influence of polarizer. In 2006, Chong *et al.*[5] carried out a study on the ANDi fiber laser. They used a plug-in one-half wave piece and a quarter-wave plate as a polarization controller to realize pulse modulation, and obtained stable self-mode-locked pulses with a pulse duration of 170 fs. In 2011, C. M. Ouyang *et al.*[6] reported on an all-fiber nonlinear polarization rotation (NPR) passively mode-locked Er-doped fiber laser in the large normal dispersion regime with pulse energy 12 nJ and pulse duration 30.5-ps output. However, the Yb-doped mode-locked fiber laser is different from the Er-doped mode-locked fiber laser. On the one hand, the standard single mode fiber (SMF) has anomalous dispersion in a 1.5-μm wavelength region for Er-doped fiber laser, and anomalous dispersion at 1.3-μm wavelength region for Yb-doped fiber laser. On the other hand, the Er-doped gain fiber has a narrow gain bandwidth which functions as an effective spectral filter in the laser, and the Yb-doped gain fiber laser has a wide gain bandwidth of more than 50 nm. As a result, the characteristics of the mode-locked pulse outputs are different from each other to some extent. Recently, many Yb-doped ANDi NPR mode-locking fiber lasers have been studied experimentally. In 2008, Schultz *et al.*[7] reported an all-fiber femtosecond Yb laser without dispersion compensation consisting of all-normal dispersion fibers. Mode-locking was achieved by nonlinear polarization evolution in combination with additional amplitude modulation generated by a fiber-based spectral filter. In 2009, experimental results on an all-fiber, all-normal dispersion Yb ring laser were reported.[8] It produced stable mode-locking of 10-ps pulses. In 2011, Zhang *et al.*[9] reported the generation of a mode-locked dis-

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sipative soliton pulse from an all-fiber Yb-doped fiber laser based on NPR without dispersion compensation or an additional filter. In 2011, Lin *et al.*[10] achieved passively mode-locked pulse generation with a giant spectrum bandwidth of more than 50 nm and pulsewidth of about several nanoseconds in an all-normal-dispersion Yb-doped fiber laser using NPR. Now many researchers are carrying out ANDi mode-locking fiber laser experiments, but theoretical research on Yb-doped all-fiber ANDi mode-locking lasers is rare.

In this paper, a Yb-doped all-fiber ANDi mode-locked fiber laser is studied in theory and experiment. Firstly, we describe the transmission characteristics of the pulse in fiber using the coupled nonlinear Schrödinger (CNLS) equation. A model for isolator and polarization controller (PC) is developed to describe the mode-locked dynamics in fiber, which shows that stable mode-locking depends on the alignment of the PCs along the fast-polarization axis of the fiber, the birefringence intensity (PC strength on the fiber), and the net cavity dispersion. Secondly, based on the theory analysis, stable mode-locked pulses are demonstrated experimentally. As a result, a mode-locked pulsed laser at 1039 nm with pulse duration 300 ps and average output power 33.9 mW (accounting for 60% of output of the coupler) at a repetition rate of 36 MHz is obtained.

2. Theory analysis

In this section, we develop a theoretical model describing the mode-locking dynamics properties of an ANDi mode-locking fiber laser. By using NPR, stable mode-locked pulses of ANDi fiber laser have been achieved.[11,12] The system consists of a polarization-dependent isolator, two embedded polarization controllers (PC1, PC2), a (976/1064)-nm wavelength division multiplexer (WDM), a 40:60 couple-ratio output coupler (OC), and a highly doped single-mode gain fiber. All-fiber devices are used in the cavity, which make the system work in a stable state. In the whole mode-locking process, pulses transmit mainly in fibers, so the interaction between the light field and the fiber medium is a key point. And the dispersion and nonlinear effects have a great influence on the mode-locked pulses.

Firstly, the numerical simulation of the experimental setup is simplified into two parts: the characteristics of light pulses transmitting in fibers and the effects of isolator and PCs on the pulses. With the CNLS equation, we deduce the ordinary differential nonlinear coupled equations describing the transmission characteristics of the pulses in fibers[13,14]

$$\frac{\mathrm{d}P}{\mathrm{d}z} = \frac{BI}{3}\eta \sin(2P)\sin(2\psi), \tag{1a}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}z} = -\frac{4}{3}BI\eta \cos(2P)\sin^2(\psi) + 2K, \tag{1b}$$

$$\frac{\mathrm{d}\eta}{\mathrm{d}z} = -2\beta\eta, \tag{1c}$$

$$\frac{\mathrm{d}\beta}{\mathrm{d}z} = \frac{2}{\pi^2}\left\{\eta^4 - \pi^2\beta^2 - I\eta^3\left[1 - B\sin^2(2P)\sin^2(\psi)\right]\right\}. \tag{1d}$$

The variable P represents the polarization angle relative to the fast-axis of the fiber, ψ is the phase difference between electric field perpendicular polarization components, η is the fluctuation factor and c is the chirp. The birefringence strength is given by the parameter K, and the variable z is the physical distance divided by the dispersion length $Z_0 = (2\pi c)/(\lambda_0^2 D)(T_0/1.76)^2$. We assume that PCs and the isolator are of periodic rotation, which are applied instantaneously at the points $Z = nL$, where L is the loop length and n takes integral values. Then we obtain that[15–17]

$$P_+ = \tan^{-1}[\alpha \tan(P_- - \theta)] + \theta. \tag{2}$$

Here, P_- and P_+ are introduced as the polarization angles relative to the fast-axis in front of (–) and in rear of (+) the polarizer, respectively. The variable α represents the attenuation factor, $\alpha = 0.01$.

We develop the mode-locking dynamic model of the laser pulses using ordinary differential equations (Eqs. (1a)–(1d)) and Eq. (2), and calculate and simulate these equations theoretically with the fourth-order Runge–Kutta method. The intracavity dispersion (D), birefringence strength (K), the angle (θ) between the pulsed polarization component and fiber fast axis, the angle (ψ) between the polarizer and fiber fast axis are discussed, which determine the mode-locking process. The parameter values used in the numerical simulation are given in Table 1.

Table 1. Parameter values in simulation.

Parameter	Value	Parameter	Value
λ_0	1.04 μm	L_{cavity}	5.6 m
T_0	400 fs	K	0.1
$\bar{D}$	30 ps/(km-nm)		

When K, θ, and ψ are fixed, the value of D gradually increases in the numerical simulation just as shown in Figs. 1(a)–1(c). From the results, we can see that the images of simulated pulse mode-locked pulse sequences are more and more uniform when the net dispersion increases, with other parameters fixed, which means that the mode-locking tends to be stable with the increase of cavity dispersion. The results are in agreement with some other experimental results reported before, that is, it is easier to obtain stable mode-locking with a long cavity since long cavity will increase the net cavity dispersion.[18]

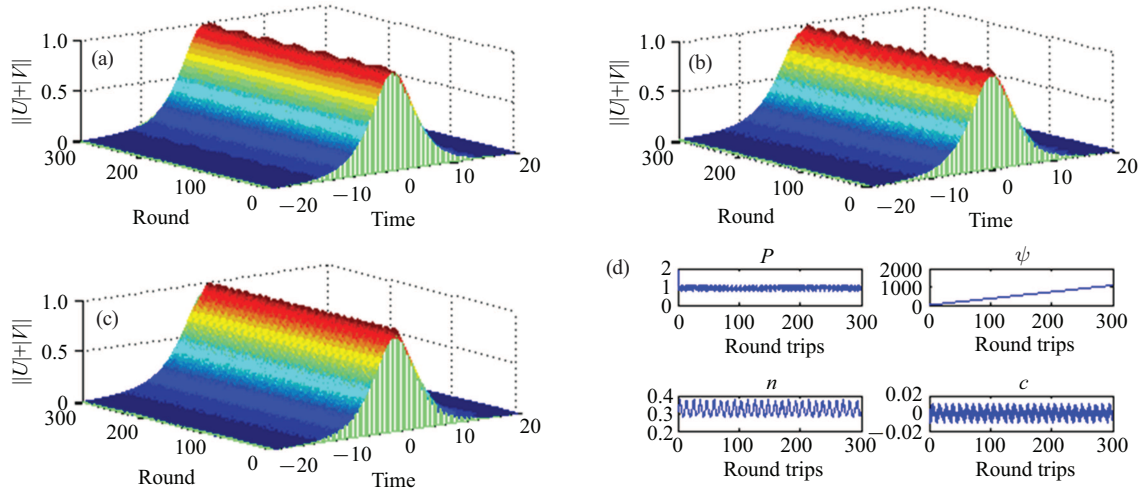
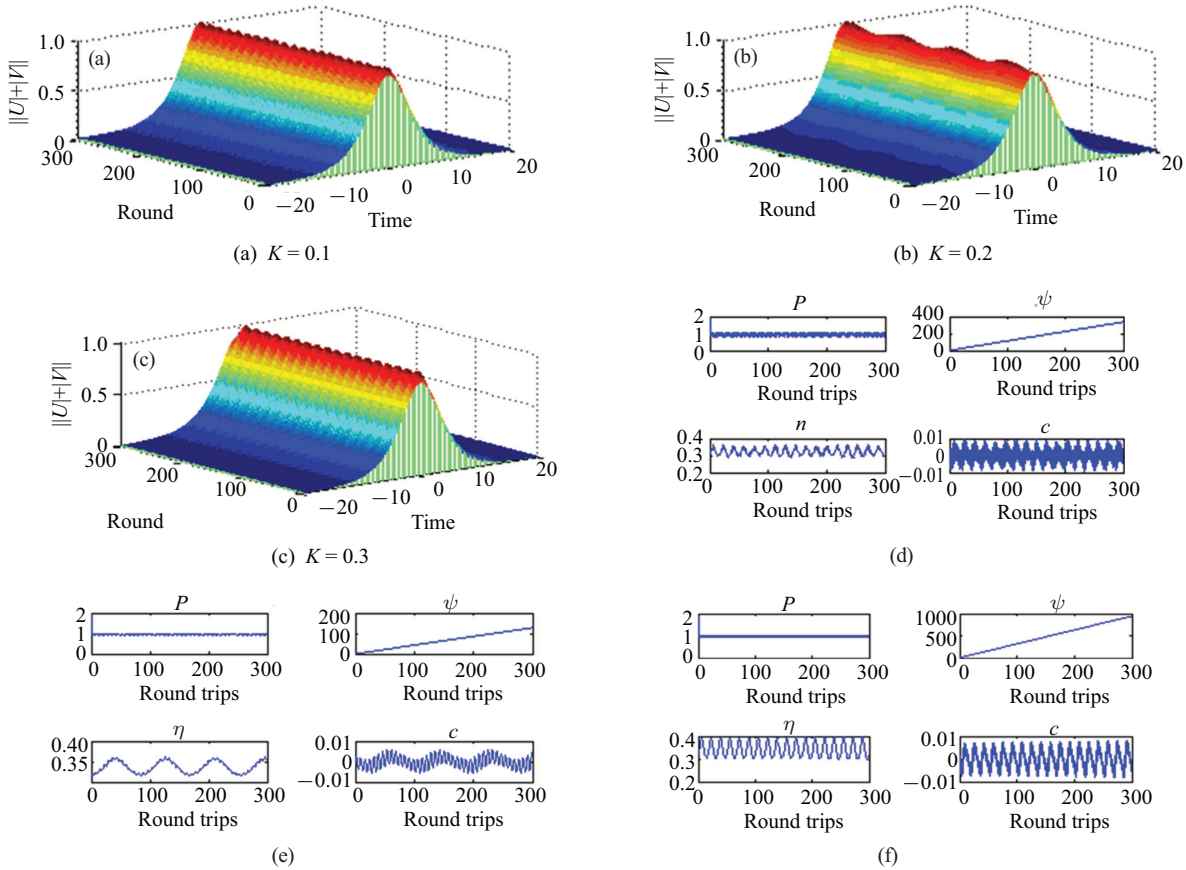


Fig. 1. (color online) Analog mode-locked pulse trains: D gradually increases ((a)–(c)), with other parameters fixed; and simulation image of cavity parameters P, ψ, η, and c (d) corresponding to panel (c).

When intracavity dispersion D, θ, and ψ are given, the value of K gradually increases in the numerical simulation as shown in Figs. 2(a)–2(c). Mode-locked pulse trains do not have a certain trend with the increase of birefringence intensity value. We can infer that there is an optimal value for the birefringence intensity K corresponding to the fixed intracavity parameters D, θ, and ψ. When they are matched, a stable mode-locked pulse will be obtained. In Figs. 2(d), 2(e), and 2(f) we show the simulation images of cavity parameters P, ψ, η and c corresponding to Figs. 2(a), 2(b), and 2(c) respectively. As shown in Fig. 2(e), it can be seen when the K matches D, a stabler state will appear, especially in the performance of chirp c. It is shown that the stronger pressure is added in the PCs, the more easily the mode-locked pulse is realized and the better quality spectrum can be obtained. Because the pressure generated by the polarization controller on the fiber is proportional to fiber birefringence intensity to some extent.



(a) $K = 0.1$ (b) $K = 0.2$ (c) $K = 0.3$

Fig. 2. (color online) Analog mode-locked pulse trains, with K being 0.1 (a), 0.2 (b), 0.3 (c), and other parameters being fixed. Panels (d), (e), and (f) show the simulation images of cavity parameters P, ψ, η, and c corresponding to (a), (b), and (c) respectively.

Now, we examine the cases where D and K are given but the values of θ and ψ are changed. Shown in Figs. 3(a) and 3(b) are the cases where $\psi = 0.6\pi$ and θ is 0 degree or 90 degree, which means the polarizer and the fiber fast axis are parallel or perpendicular to each other, thus stable mode-locking cannot be produced. It is consistent with the polarization rotation principle, by which a polarizer is used to convert linearly polarized light into elliptically polarized light, thereby achieving the modulation for mode-locking. So when the polarizer and the fiber fast axis are parallel or perpendicular to each other, linearly polarized light is not converted into elliptically polarized light and mode-locking cannot be realized.[19] Figures 3(c) and 3(d) show the simulation images for stable mode-locking when θ and ψ have appropriated values as indicated in the figure.

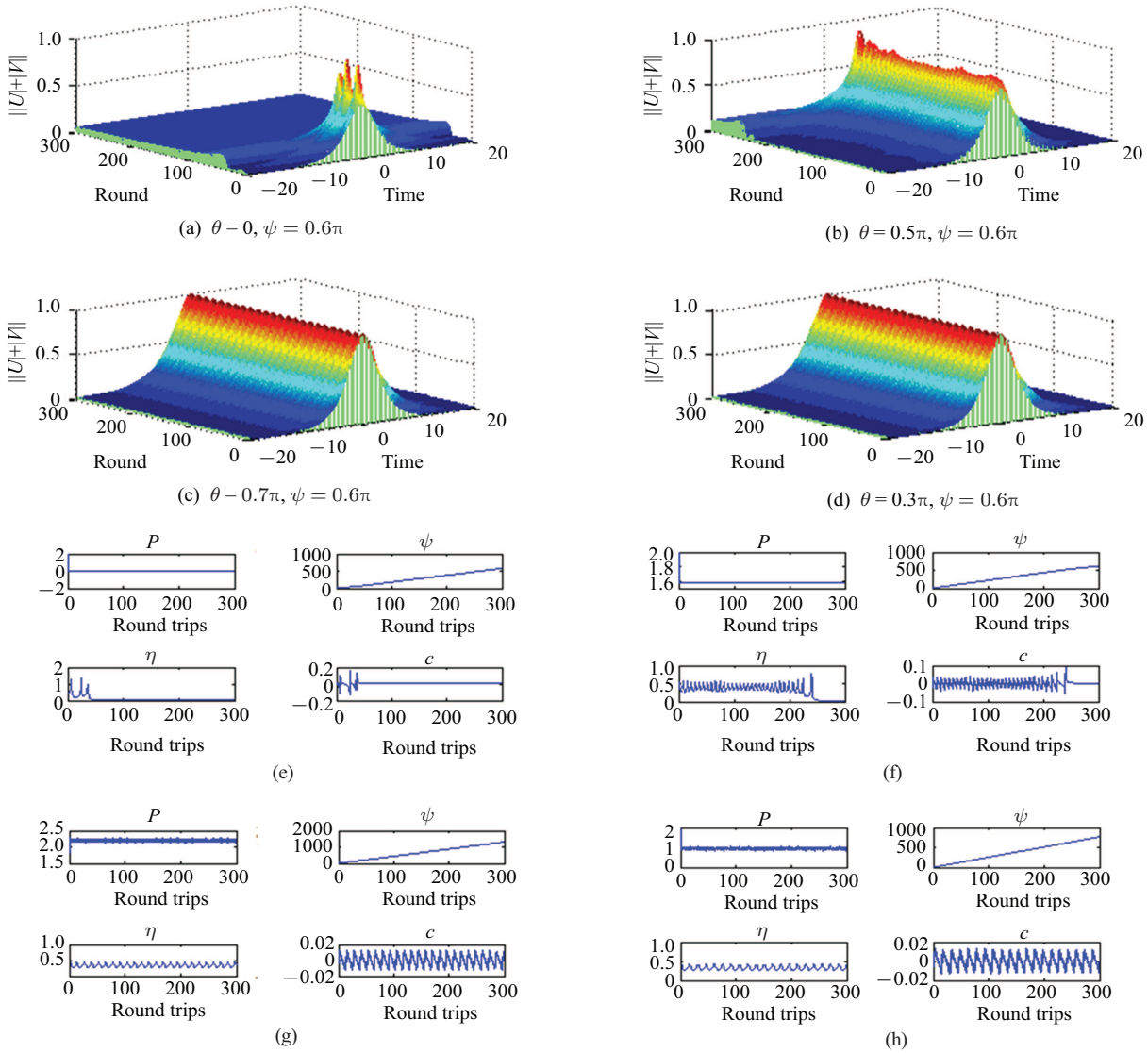


Fig. 3. (color online) Analog mode-locked pulse trains: θ and ψ are changed, when other parameters are given; panels (e), (f), (g), and (h) show the simulation images of cavity parameters P, ψ, η, and c corresponding to panels (a), (b), (c), and (d) respectively.

3. Experiments and results

The experimental setup of the NPR mode-locking fiber laser is shown in Fig. 4. A ring cavity is used with a total length of 5.6 m. A long cavity can increase the net cavity dispersion, which makes obtaining stable mode-locking easier according to the theoretical analysis. In the experiment, the pump source operates at a central wavelength of 976 nm and its maximum output power is 556 mW. The highly Yb-doped single-mode gain fiber (Nufern YSF-HI, 976 nm, absorption rate of 250 dB/m) is chosen to be 1 m in length.

Based on theoretical analysis, we firstly adjust the pressure of the polarization controller knob to make the output power reach a maximum value, and then adjust the angle of PCs also to let the output power arrive at a maximum value. Secondly, we observe the pulse signals on an oscilloscope by increasing the input power gradually to find the scope of the

mode-locking threshold. Finally, repeating the above steps, we can achieve stable mode-locking pulses in a particular state. When we inject a pump power of 320 mW, stable mode-locked pulse trains are obtained. The repetition rate is 36 MHz, which is consistent with the theoretical value of 5.6-m cavity length. By continuing to increase the pump power to 556 mW, we then obtain a maximum output power of 33.9 mW and repetition rate remains unchanged. Figure 5 shows the results of stable mode-locked pulse trains detected by the digital oscilloscope (Tektronix TDS305413).

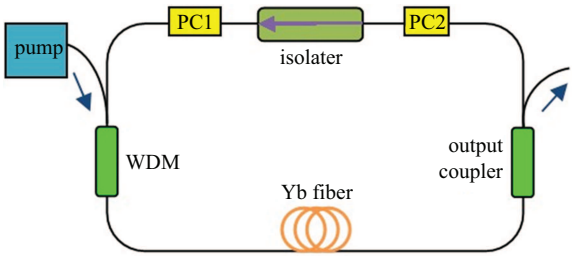


Fig. 4. (color online) Experimental setup of the ANDi Yb-doped mode-locked fiber laser.

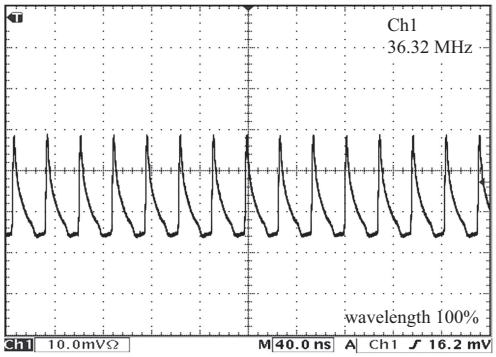


Fig. 5. Mode-locked pulse train of the ANDi Yb-doped mode-locked fiber laser.

In experiment, we find that the stable mode-locking pluses do not mean the maximum pressure of the PC's knob, but it is at an appropriate value. It coincides with our theoretical analysis that there is a correspondence between the birefringence intensity K (pressure of PC) and the intracavity dispersion D (cavity length) when the stable mode-locking pluses are achieved. Besides, it shows that it is easier to achieve stable mode-locking pulses with a long cavity, and cavity net dispersion could be directly controlled through the cavity length. So we obtain the conclusion that big net cavity dispersion can easily achieve stable mode-locking pulses, which is in agreement with our theoretical analysis. We further find that the spectral width can be changed by adjusting the PC. In the case where the laser is mode-locked, slightly tuning one PC paddle clockwise (counterclockwise), the spectral width increases (decreases). Further tuning the PC will break up the mode-locking states when the spectrum width reaches the maximum (minimum). As shown in Fig. 6, the 3-dB bandwidth of the spectrum is 6 nm and the spectral curve is very smooth. In Fig. 7, the 3-dB bandwidth of the spectrum is about 10 nm and the spectral curve is not better than that above. The width can be changed from 6 nm to 10 nm continuously, and the spectral shape is nearly invariant. This tunability is caused by the filter effect in the laser. A spectral filter effect exists in mode-locked laser due to NPR, and the filter width depends on the birefringence of the fiber. That is, the NPR can be considered as a filter, since the accumulated chirp is so large. The characteristics of the maximum transmission wavelength and the transmission bandwidth can be changed through changing the element state of the NPR, which is polarized. Here, when tuning the PC, the birefringence magnitude is changed, which results in the variation of the bandwidth of the filter. Finally, the spectral width of the pulse is tuned. In addition, we cannot observe that the spectrum exhibits steep edges, but we see a parabola-like curve. It is mainly because what we obtained is an ANDi mode-locked laser and not an ANDi dissipative soliton mode-locked laser, which will result in a steep spectral edge. We do not introduce any filer into our experimental device and this all-fiber laser has a low output power, consequently, it cannot reach the threshold of dissipative soliton mode-locking.[20] The pulse width 300 ps of the laser is measured by a high speed digital oscilloscope (LyCroy 10 GHz) and the result is shown in Fig. 8. Here, it should be pointed out that the 300 ps of pulse width is beyond measuring range of our APE autocorrelator.

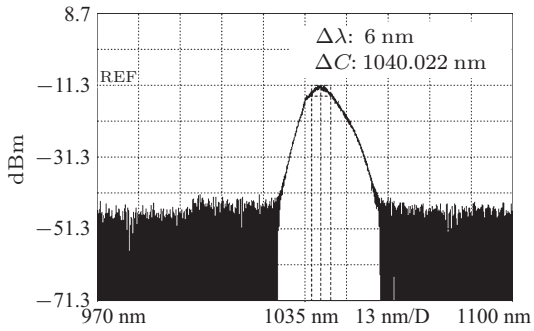


Fig. 6. Output spectrum of the ANDi Yb-doped mode-locked fiber laser, with $\Delta\lambda = 6.000$ nm.

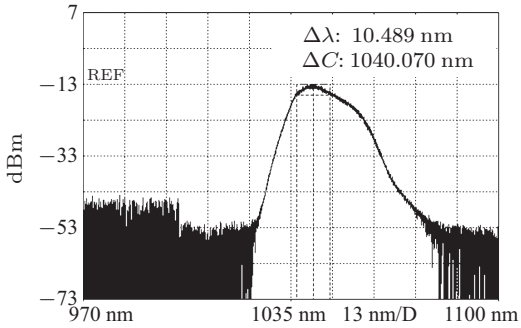


Fig. 7. Output spectrum of the ANDi Yb-doped mode-locked fiber laser, with $\Delta\lambda = 10.489$ nm.

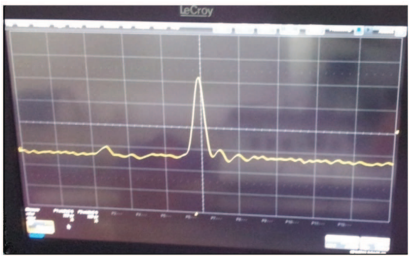


Fig. 8. (color online) Pulse width of the ANDi Yb-doped mode-locked fiber laser detected by a high speed digital oscilloscope (LyCroy 10 GHz) : $P = 300$ ps.

4. Conclusion

An all-fiber ANDi Yb-doped mode-locked fiber laser is studied in theory and experiment. A model simulating the normal dispersion fiber ring laser mode-locked dynamics is developed, which shows that the achievement of stable mode-locking depends on the alignment of the PCs along the fast-polarization axis of the fiber, the birefringence intensity, and the net cavity dispersion. With theoretical analysis, stable mode-locked pulses with pulse duration 300 ps and average output power 33.9 mW at repetition rate 36 MHz are obtained.

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