All-fiber normal-dispersion single-polarization passively mode-locked laser based on a 45°-tilted fiber grating

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Abstract: An all-fiber normal-dispersion Yb-doped fiber laser with 45°-tilted fiber grating (TFG) is, to the best of our knowledge, experimentally demonstrated for the first time. Stable linearly-chirped pulses with the duration of 4 ps and the bandwidth of 9 nm can be directly generated from the laser cavity. By employing the 45° TFG with the polarization-dependent loss of 33 dB, output pulses with high polarization extinction ratio of 26 dB are implemented in the experiment. Our result shows that the 45° TFG can work effectively as a polarizer, which could be exploited to single-polarization all-fiber lasers.

OCIS codes: (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium; (140.4050) Mode-locked lasers.

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1. Introduction

Passively mode-locked fiber lasers have attracted considerable interest and been extensively investigated in the past two decades for their compact configuration, economy, low thermal effect, and good flexibility [1–3]. Various mode-locking techniques including semiconductor saturable absorber mirrors [4–6], nonlinear optical loop mirror (NOLM) [7, 8], and nonlinear polarization rotation (NPR) [9–12] have been used to generate ultrashort pulses. All these techniques have the common features of saturable absorber in which the pulse wings experience more loss than the center part does. However although solid-state mode-locked lasers remain the current workhorse for high-power ultrashort pulse generation for applications, those lasers are not up to integrability with other telecom components. The all-fiber format without coupling between fiber and bulk segments has great stability, compact design and low insertion loss. An intense effort, therefore, is now carried out to implement the all-fiber configuration. The carbon nanotube [5] and graphene [6] methods which can accomplish the all-fiber configuration have recently been intensively investigated. Those methods are not competent for the large power output because of the limited optical damage threshold and modulation capabilities of these absorbers [13]. NPR technique can overcome those limits, but most of investigations based on the bulk optical polarizer sacrifice the benefits of all-fiber format. D. Panasenko *et al.* had replaced the bulk optical polarizer with a segment of polarization fiber [14]. The 45° TFGs that can discard the s-polarization component from fiber core and leave the p-polarization component propagating in the fiber core with minimum loss have attracted great interests [15–18]. Based on 45° TFGs, a series of optical fiber devices have been reported, such as PDL compensator, polarization equalizer polarimeter, and filter [15, 19–22]. However, the 45° TFG is rarely used as a polarizer in the passively mode-locked fiber laser. To our best knowledge, most researches focus on the Er-doped fiber lasers employing the 45° TFG in the recent two years [13, 23]. We firstly report the generation of dissipative solitons (DS) in a passively mode-locked Yb-fiber laser employing a 45° TFG polarization element in this manuscript. The formation of DSs is a balance result of group velocity dispersion, self-phase modulation, gain and loss, as well as spectral filtering [24].

In our experiment, self-started mode locking of the laser can be achieved by employing a 45° TFG with 33 dB PDL when the pump power is increased above 196 mW. The 4-ps pulses with 9-nm bandwidth are directly generated from the cavity. Consequently, the corresponding time bandwidth product (TBP) is estimated as ~10. The laser emits pulses with characteristic sharp-edges optical spectrum. Moreover, the parabolic phase profile in temporal domain denotes that the pulses with linear chirp can be compressed. Adjusting the polarization controller (PC) outside of the laser cavity, the polarization extinction ratio (PER) of output pulses is measured as ~26 dB, which indicates that the pulse is linearly polarized. Linear polarization is an attractive feature in optical parametrical devices, interferometric fiber sensors, active crystals, and nonlinear frequency conversion [25]. Up to now, several methods to obtain single-polarization operation of fiber laser have been reported, for example, distributed feedback fiber lasers, the fiber Bragg gratings polarization selection technique and so on. In this paper, we provide a novel and simple method for achieving single-polarization pulses. The 45° TFG has many merits such as high PDL, high damage threshold, and wide operating bandwidth, which can compare favorably with the commercial fiber and bulk polarizers. Accordingly, the 45° TFG paves a new way for the realization of stable, compact, single-polarization, high-power, and all-fiber ultrashort-pulse laser sources.

2. Characterization of 45° tilted fiber grating

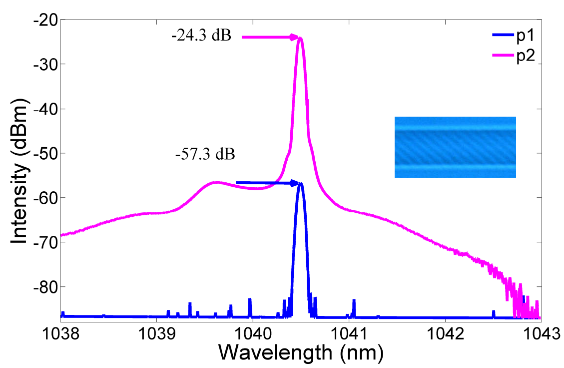

Fig. 1. Transmission spectra of the 45° TFG at 1040.5 nm measured at two orthogonal polarization states. Inset: microscope image of the 45° TFG.

The 45° TFG is UV-inscribed using the phase-mask scanning technique and a frequency-doubled Ar laser. This method of fabrication can be used for various fibers. The standard single mode fiber (SMF) is inscribed in this experiment. Fabrication and measuring PDL of 45° TFG have been described in detail in reference 18. The microscope image of the 45° TFG is shown in the inset of Fig. 1. Based on the measurement setup shown as Fig. 8 in reference 18, we can adjust the PC to launch the light with two orthogonal polarization states (p1, p2) to obtain the maximum and minimum transmission spectra of 45° TFG, which is shown in Fig. 1. The 33 dB difference between the maximum and minimum transmission profile is the PDL of 45° TFG at 1040.5 nm. In general, the commercial fiber polarization dependent isolator has

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25 dB PER and 30 nm operating bandwidth. For the 45° TFG, the operating bandwidth is beyond 100 nm [18]. The polarizer with high PER and wide operating bandwidth shows the superiority for the passively mode-locked fiber laser based on NPR technology. Therefore, this 45° TFG can prevent the competition of polarization mode without limiting the spectrum of output pulses. In order to implement the high output power, we will inscribe the dual-clad fiber based on this method.

3. Experimental setup

The configuration of the fiber laser is schematically shown in Fig. 2. It consists of a segment of 45° TFG, a 980/1053 nm wavelength-division-multiplexed (WDM) coupler, a 0.7-m long YDF with absorption coefficient of 500 dB/m at 976 nm, a polarization insensitive isolator (PI-ISO) with bandwidth of 10 nm at 1053 nm center wavelength, a fused optical coupler (OC) with 10% output, two set of PCs, and the standard SMF. The total length of cavity is 7 m, and the fundamental frequency of cavity is 29.6 MHz corresponding to the pulse separation of about 33.7 ns. The dispersion parameters for YDF and SMF are 20 ps^2/km and 22.1 ps^2/km at 1050 nm, respectively. A 980 nm laser diode is used to provide the pump. A 45° TFG and two PCs act as an equivalent saturable absorber for mode-locking operation. An ISO with 10-nm filter is used to make the light propagate unidirectionally in the cavity and promote the pulse formation. The polarization state of output pulse is further studied by employing a bulk polarization beam splitter (PBS) and a PC. The PER of the PBS is 40 dB. The output properties of the laser oscillator are monitored by an optical spectrum analyzer (AQ-6315A, ANDO), a digital storage oscilloscope (Model 8600, LeCroy) with 6-GHz-bandwidth, a radio-frequency (RF) analyzer (Agilent E4447A), a power meter, and a frequency-resolved optical gating (Mesa Photonics, 1CUS).

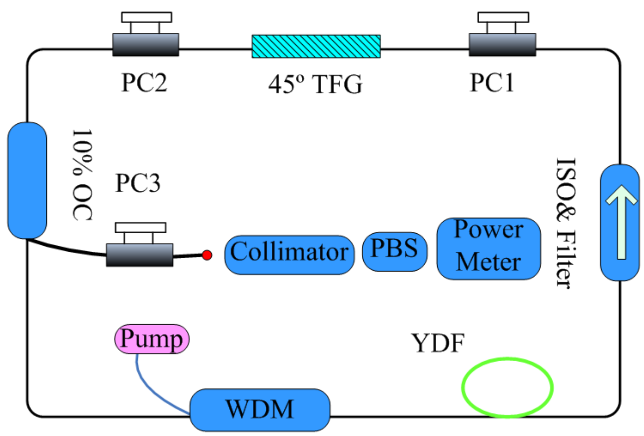

Fig. 2. Experimental setup of the fiber ring laser.

4. Experimental results and analyses

The 45° TFG compels the light leaving fiber grating to be in linear polarization state. The rotation angle is proportional to the area of the polarization ellipse, thus linear polarization light does not experience polarization rotation in the fiber laser. By adjusting the PC1, the linear polarization light changes into the elliptical polarization state. The nonlinear phase induced by self-phase modulation and cross-phase modulation impose the orthogonally polarized components, so the state of light will evolve in the total laser cavity. The state of polarization is nonuniform across the pulse because of the intensity dependence of the nonlinear phase. The PC2 forces the polarization direction of center part of pulse is identical to that of the 45° TFG. Thus, the 45° TFG lets the center part of pulses pass and blocks the

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pulse wings. Consequently, the 45° TFG and two PCs can act as an artificial saturable absorber to utilize to realize self-starting passive mode locking.

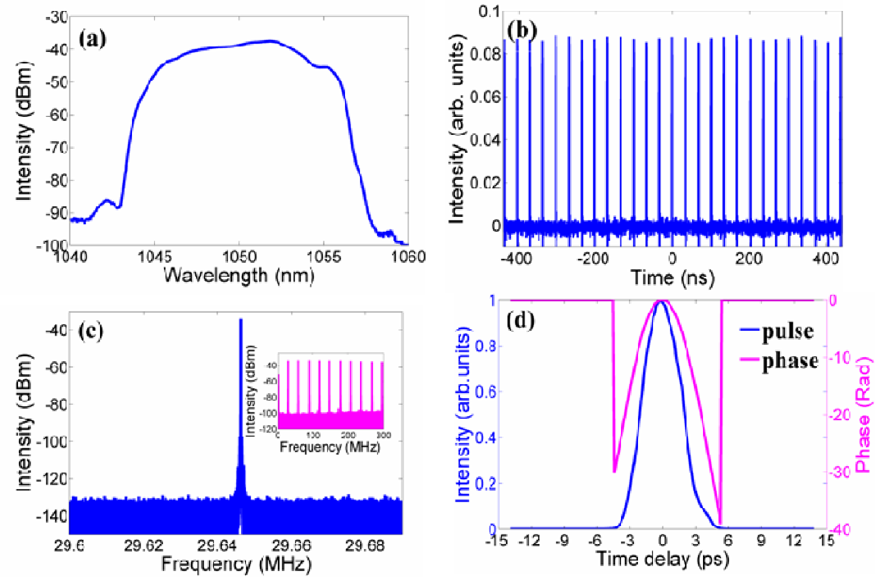

Fig. 3. Optical spectrum (a), oscilloscope trace (b), RF spectra (c), and pulse and phase profile (d) at 196 mW.

By adjusting the PCs with appropriate orientation and pressuring settings, single pulse emission can be easily achieved when the pump power is above 196 mW. The optical spectrum, pulse sequence, RF spectra, pulse profile and phase in temporal domain at 196 mW are shown in Figs. 3(a)-3(d), respectively. The optical spectrum centered at 1050 nm is shown in Fig. 3(a), where the 3-dB width is estimated as ~9 nm. The spectrum profile has steep edges, which is the typical characteristic of normal-dispersion pulse. Steep spectrum edges are limited by the effect of gain spectral filtering and the physical filter bandwidth. Figure 3(b) shows that the pulse train is quite uniform with pulse-pulse separation of 33.7 ns. The quite uniform of pulse sequence is attributed to the soliton energy quantization effect [26]. As shown in Fig. 3(c), the 29.646 MHz fundamental cavity repetition rate at a resolution bandwidth of 100 Hz has a signal-to-noise ratio of ~80 dB. The fundamental cavity repetition rate is in good agreement with pulse-pulse separation. The 80-dB signal-to-noise ratio proves the mode locking to be stable. The inset of Fig. 3(c) shows RF spectra in the range of 300 MHz bandwidth have the constant height of the peaks and the flat noise-underground at −130 dB, which denotes that no q-switching or harmonic solitons are present. The blue and magenta curves in Fig. 3(d) represent the pulse profile and phase in temporal domain, respectively. Taken on the Gaussian fit, the pulse duration is evaluated as 4 ps. Hence, the corresponding TBP is about 10, which describes the pulse is chirped. The parabolic profile phase in the temporal domain represents the pulse has positive linear chirp [27], which can be compensated by negative-dispersion elements such as gratings [28], photonic crystal fiber [29], higher-order mode fibers [30], and chirped Bragg gratings [31]. Decreasing the pump power to 160 mW, the laser is also in stable mode-locked state due to hysteresis phenomena. This laser can be in stable mode-locking state beyond 24 hours.

The formation mechanism of pulses in the all-normal dispersion fiber laser is different from that of the conventional solitons and dispersion-managed solitons. In all-normal dispersion region, the positive linear chirp prevents the generation of a nonmonotonic chirp [32]. When the nonlinear phase is strong enough to conquer the linear chirp, dissipative solitons will break. Mode-locked pulses delivered from all-normal dispersion fiber laser usually exhibit broad pulse width, which decreases the peak power of pulse and nonlinear

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phase. Thus, the output pulse energy of DSs can realize a remarkable increase. The formation of DSs is generally understood as a balance result of saturable absorption, group velocity dispersion, self-phase modulation, gain and loss, as well as spectral filtering. Moreover, the 45° TFG and two PCs functioning as an artificial saturable absorption promotes the formation of DSs.

The polarization state of the DS is investigated by employing a bulk PBS and a PC external to the cavity, as shown in Fig. 2. The bulk PBS with 40 dB PER is used to resolve the two orthogonally polarized components. The PC3 controls the linear birefringence of fiber. The power meter monitors the power from one output port of the PBS. Adjusting the PC3, the PER of output pulses is calculated as ~26 dB by measuring the maximum and minimum output power, which indicates the pulse is nearly totally polarized. The PER of output pulse is lightly less than the PDL of 45° TFG due to the output coupler with non-polarization maintaining fiber pigtail. The single-polarization output pulse is desired for different applications such as optical parametrical devices, interferometric fiber sensors, pumping of active crystals, and non-linear frequency conversion. Compared with commercial fiber or bulk polarizers, the 45° TFG possesses the born preponderance: high PDL, high damage threshold, and wide operating bandwidth. Therefore, the 45° TFG and two PCs function as an artificial saturable absorption, which offers an attractive opportunity to implement stable, compact, high-power, single-polarization and all-fiber ultrashort-pulse laser sources. Furthermore, all-fiber polarization interference filter based on the 45° TFG can also help to achieve multiple-wavelength laser [33].

5. Conclusions

We have experimentally demonstrated dissipative solitons delivered from an all-normal dispersion Yb-fiber laser based on the 45° TFG. Mode-locked DS with the duration of 4 ps and bandwidth of 9 nm is obtained. The corresponding time-bandwidth product of ~10 indicates that the output pulse is chirped, while the parabolic phase profile denotes the chirp is nearly linear across the pulse. The measured PER of output pulse is ~26 dB, which denotes that the pulse operates in the single-polarization state. Experimental results reveal that the 45° TFG together with two PCs can work as an equivalent saturable absorber and help to the realization of self-started mode locking. As a result, the 45° TFG can pave a new way for the realization of stable, compact, high-power, single-polarization and all-fiber ultrashort-pulse laser sources.

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