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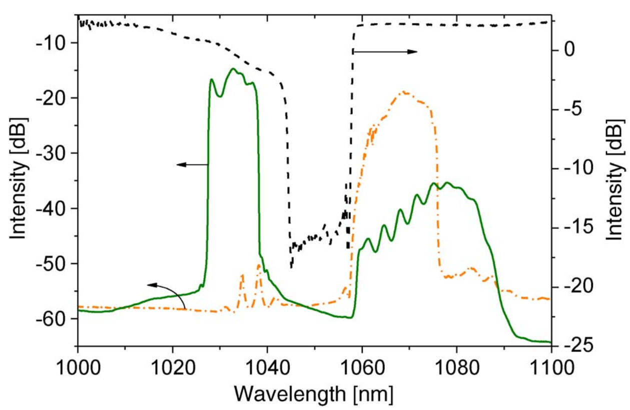

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Wavelength-Switchable Dissipative Soliton Fiber Laser With a Chirped Fiber Grating Stop-Band Filter

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Abstract: We report a wavelength-switchable single-polarization dissipative soliton (DS) mode-locked fiber laser using a chirped fiber Bragg grating (FBG) for spectral filtering. The chirped FBG, when inserted into the ring cavity, provides a stopband from 1045 nm to 1057 nm, which is used for spectral filtering in this all-normal-dispersion mode-locked Yb-doped fiber laser. The combination of the chirped FBG and the Yb gain profile help the formation of the DS. The laser delivers wavelength-switchable and polarized (28 dB) DS of 6.1 nJ and 29 ps at 1032 nm, and 4.3 nJ and 24 ps at 1068 nm, respectively. To the best of our knowledge, this is the direct proof that a bandpass filter is not indispensible to achieve stable DS in ps fiber lasers.

Index Terms: Fiber lasers, mode-locked lasers.

1. Introduction

Recently, dissipative soliton (DS) mode-locked fiber lasers have been extensively investigated owing to their high pulse energy and linearly chirped pulse, which can be further compressed. The mode-locking mechanism had been attributed to strong spectral filtering of the highly chirped pulse described as DS. The pulse energy can be scaled up to 20 nJ with a pulsewidth of $<$ 200 fs from a single-mode fiber laser [1]. Several fiber-based bandpass filters have been reported for realizing stable DS mode-locked output, e.g., fused wavelength division multiplexer [2], [3], Lyot filter [4], sagnac loop filter [5], and multimode interference filter [6]. In some case, DS could be observed in a mode-locked laser without a real bandpass filter, in which the gain spectrum of erbium [7] or the birefringence-induced filter effect [8] plays role of filtering in forming the stable mode-locked output. A tilted fiber Bragg grating (FBG) was also used together with a semiconductor saturable absorber mirror (SESAM) to achieve DS operation [9], in which SESAM provided mode-locking mechanism.

The important role of the filter in all-normal-dispersion mode-locked fiber laser resulted in many interesting publications, especially in different DS operations. Zhang *et al.* first reported multi-wavelength DS in a fiber laser mode-locked with SESAM [10]. Yue *et al.* observed dual-wavelength DS in a mode-locked figure-eight fiber laser operating in the net-normal dispersion regime [11]. Li *et al.* demonstrated 12-nm tunable DS operation, mode locked by single-walled carbon nanotube

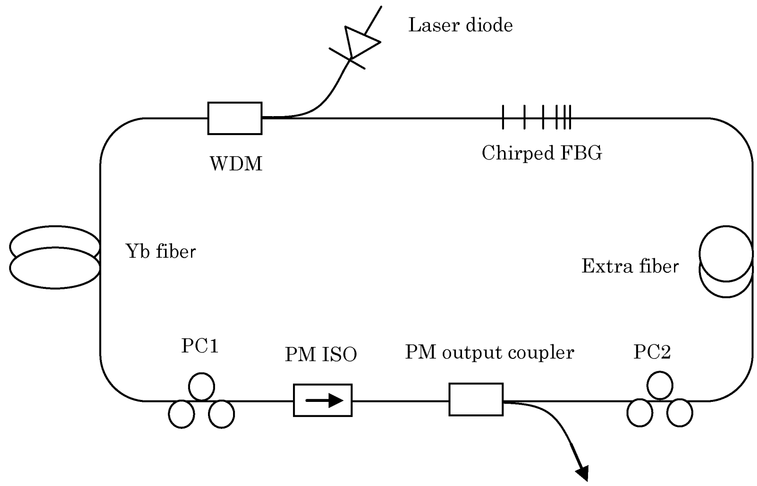

Fig. 1. Schematic diagram of the mode-locked fiber laser.

(SWCNT) absorber [12]. However, the invisible birefringence-induced bandpass filter in [10]–[12] depends greatly on the precise parameters of the laser cavity to achieve wavelength variation operation, which make it difficult to assess the effects of filter parameters on the DS operation. The Lyot filter with a periodic transmission spectrum in the ring cavity is easy to implement [4]. Utilizing its periodic transmission spectrum, Fedotov *et al.* reported pulsewidth and wavelength-switchable all-fiber mode-locked Yb laser with SWCNT [13]. Zhang *et al.* obtained tunable and switchable dual-wavelength DS generation with the similar configuration [14]. However, the transmission spectrum of the Lyot filter is also sensitive to the laser polarization state inside the cavity. In most cases, the periodic spectral filtering is considered to be responsible to wavelength switchable or dual-wavelength operation.

In this letter, we demonstrate a wavelength switchable DS mode locking in an all-normal dispersion Yb-doped fiber laser based on nonlinear polarization evolution (NPE). A broadband-chirped FBG is inserted in the ring cavity as a stopband filter. Highly polarized and switchable 1032-nm and 1068-nm DS are achieved. The output pulse energy of 6.1 nJ at 1032 nm and 4.1 nJ at 1068 nm, respectively, are the highest reported pulse energy for the wavelength-flexible DS, to the best of our knowledge. This work provided clear evidence that a bandpass filter is not indispensible to achieve stable DS mode locking.

2. Experimental Details

The laser setup is illustrated in Fig. 1. A piece of 30-cm-long highly Yb-doped single-mode fiber is used as a gain medium, which has nominal core absorption of more than 750 dB/m at 976 nm. The pump source is a 400-mW single-mode pigtailed laser diode emitting at 974 nm. Approximately 30% of the beam is extracted from the cavity through a PM fiber coupler placed after isolator, which insures the highly polarized output. Two polarization controllers and a PM isolator are used to provide NPE mechanism for mode locking. The chirped FBG with a stop-bandwidth of 12 nm is inserted into the ring cavity for spectral filtering of the highly chirped pulses. A piece of HI 980 fiber is inserted into the cavity to lengthen the cavity. The whole cavity length is 23 m, corresponds to an overall cavity dispersion of -0.9 ps/nm at 1032 nm and -1.04 ps/nm at 1068 nm, respectively.

The chirped FBG was fabricated into the core of a single-mode fiber (Nufern HI1060) with a chirped phase mask of a 14-nm/cm chirp rate. The FBG stopband is centered at 1051 nm with a -3-dB bandwidth of 12 nm. Since the FBG is 6.4 mm long its dispersion is 5.2 ps/nm. However, we use the FBG in transmission (spectrum shown in Fig. 3), its function is spectral filtering instead of dispersion compensation.

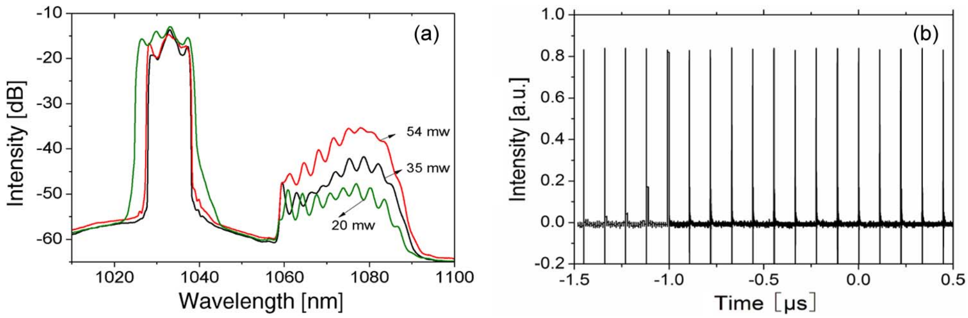

Fig. 2. (a) 1032-nm output spectra of the mode-locked fiber laser at different output power (20 mW, 35 mW, 55 mW). (b) Output pulse trains of 1032-nm mode-locked laser.

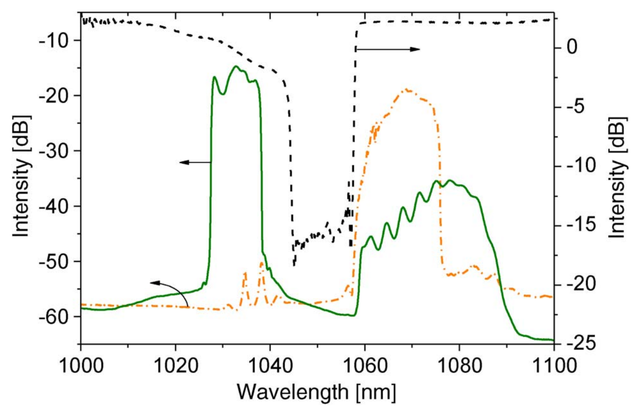

Fig. 3. Transmission spectrum of chirped FBG (dash), output spectrum of the mode-locked fiber laser at 1032 nm (solid) and 1068 nm (dash dot).

3. Results and Discussions

Mode-locked operation at 1032 nm is obtained by adjusting the polarization controllers when the pump power exceeds the threshold of about 165 mW. When we further increase the pump power, the ASE at the 1068 nm begins to increase, as shown in Fig. 2(a). However, at the maximum output power of 54 mW, the ASE light at 1065 nm is still 23 dB lower than the mode-locked lasing emission at 1032 nm. The central wavelength of the mode-locked output is 1032 nm with a -3 dB bandwidth of 9 nm. The pulse train measured with a photodiode (1-GHz bandwidth) is shown in Fig. 2(b). It exhibits a pulse spacing of 112 ns, corresponding to pulse repetition rate of 8.9 MHz. When the pump power is further increased up to $\sim$240 mW, we can achieve the mode-locking output at a wavelength of 1068 nm by adjusting the PCs. Its -3-dB bandwidth is 8 nm. At the maximum output power, the ASE at 1032 nm is still 32 dB below the mode-locked spectrum at 1068 nm. Fig. 3 shows the spectra of 1032 nm and 1068 nm mode-locked laser emissions at their respective maximum output, which exhibit sharp edges, a typical characteristic of the DS lasing by spectral filtering of the highly chirped pulse in the all-normal-dispersion regime. The laser emission spectrum at 1068 nm did not change much as the pump power increased. By adjusting the PCs, the lasing at 1032 nm and lasing at 1068 nm can be switched back and forth. The spectral shape and output power are repeatable; thus the output is not only wavelength switchable but also wavelength controllable.

The autocorrelation traces of the mode-locked pulses were measured with a commercial autocorrelator (Femtochrome FR-103XL), which give a pulsewidth of 29 ps for 1032 nm and 24 ps for 1068 nm, respectively, as depicted in Fig. 4. The radio-frequency (RF) spectra around the fundamental and harmonic repetition rates are shown in Fig. 5(a) and (b), measured with a high

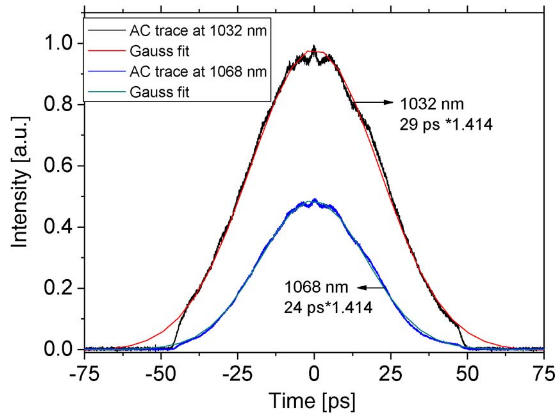

Fig. 4. Autocorrelation trace of the mode-locked laser at 1032 nm and 1068 nm.

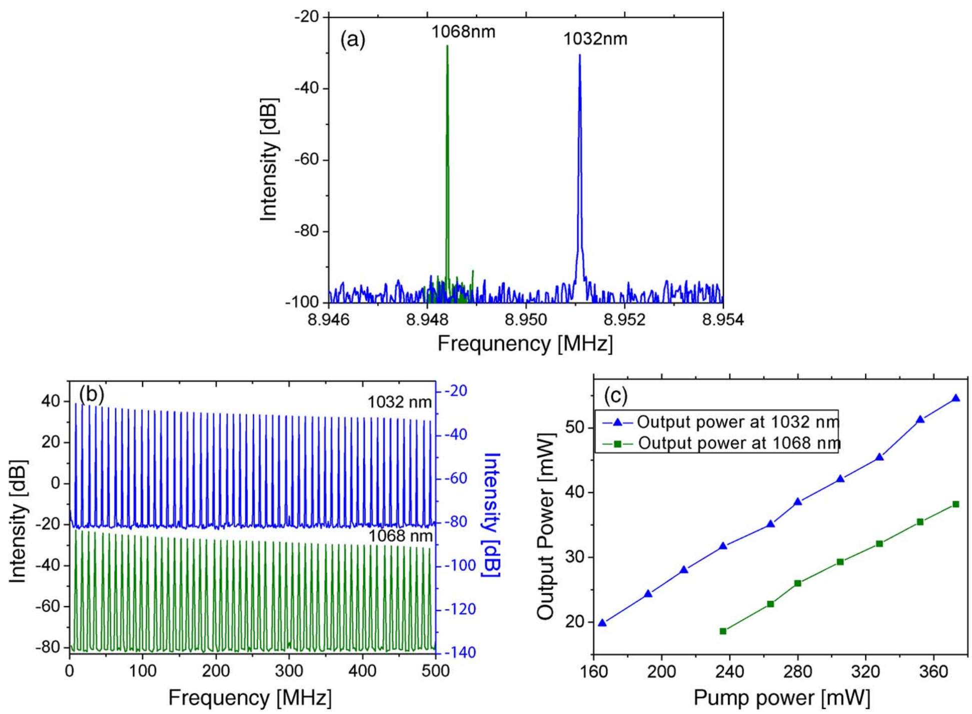

Fig. 5. RF spectrum (a) around the fundamental and (b) harmonic repetition rates at 1032 nm and 1068 nm. (c) Output power of the mode-locked fiber laser with respect to the pump power at 1032 nm and 1068 nm.

resolution RF-spectrum analyzer (Agilent, N9320B). The resolutions used were 10 Hz and 1 kHz, respectively. From Fig. 5(a), it is clear that repetition for 1032 nm and 1068 nm are 8.951 MHz and 8.948 MHz, respectively, which match well with the wavelength difference. No obvious residual sidebands caused by Q-switched mode locking could be observed. An over 65-dB signal-to-noise ratio indicates excellent mode-locking stability and low pulse energy fluctuation at these two wavelengths. Fig. 5(c) shows the output power of 1032 nm and 1068 nm as a function of the pump power. The maximum output power for 1032 nm and 1068 nm are 54 mW and 34 mW, respectively, corresponding to single pulse energy of 6.1 nJ and 4.3 nJ at a pulse repetition of 8.9 MHz. To measure the polarization extinction ratio (PER), the laser output, mounted on a rotating stage, was firstly collimated. The parallel beam was passed through a cubic polarization beam splitter, which separated two polarizations into two orthogonal directions. The laser output end was then rotated till the power of the two orthogonal beams reached the highest contrast. The high PER of 28 dB was achieved as the result of high PER of the output PM coupler.

To verify that the mode locking was indeed resulted from the filtering effect of the chirped FBG, we purposely removed it from the cavity. No dissipative mode locking could be obtained, but only noise-like pulses even with the maximum available pump power. As we know, the all-normal dispersion mode locking depends strongly on dissipative processes, such as linear gain and loss, nonlinear saturable absorption, phase modulations, and especially the spectral filtering to shape the pulse. Self-amplitude modulation occurs through spectral filtering of a chirped pulse, which cuts off the temporal wings of the pulse to stabilize the mode locking [15]. In our experiment, mode locking at 1032 nm could be easily obtained at the cavity length from 10 m to 60 m. Near 1032 nm, the relatively steep gain spectrum and the stopband of the chirped FBG provided spectral filtering, which facilitated the DS formation. However, it was difficult to obtain mode lock at 1068 nm if the cavity length was shorter than 20 m. Stable mode lock could be obtained by adjusting PCs only when the cavity is extended. This can be explained as following: though the stopband of chirp FBG and gain profile could also provide spectral filter at 1068 nm, the lasing there requires also the suppression of lasing at 1032 nm, where the gain is higher. The NPE effect could introduce wavelength-dependent loss as demonstrated in [16]; however, it may not be sufficient. When the cavity length is extended, first, the artificial birefringence filter induced by cavity birefringence has a smaller bandwidth, which may introduce higher loss at 1032 nm, and second, the longer cavity length with a low repetition rate significantly increases the pulse energy of the random surge of the background noise, which facilitates the mode-locking operation at 1068 nm [17].

It is also possible to use cFBG in reflection to manage the dispersion in ring fiber near 1 μm region provided that the equivalent β_2 of cFBG can be properly designed. The current cFBG has a β_2 value of ± 2.2 ps^2, which corresponds to the β_2 of about 100 m of HI1060 fiber. In order to compensate for fiber dispersion of between 10 to 20 m long, a phase mask with a much large chirp rate, such as between 70 to 140 nm/cm is needed for fabricating cFBG with smaller β_2 value. This kind of phase mask is currently not available on the market and has to be customer-made. In addition, the other constraint for such cFBGs is the limited photosensitivity of the fiber for such a large chirp rate.

4. Conclusion

In conclusion, we have successfully demonstrated all-fiber wavelength switchable DS operation in an all-normal-dispersion Yb-doped fiber laser. A low-insertion-loss chirped FBG has been used as a stopband filter. The laser emission wavelength is switchable between 1032 nm and 1068 nm from the combination effect of the FBG stopband filter and the Yb gain profile. Our results clearly show that, while the spectral filtering is important to achieve DS operation, the spectral width and steep edges of the laser emission spectrum come from the interaction of gain, loss, nonlinearity, and dispersion instead of from the spectral filter. The laser configuration is relatively simple for obtaining wavelength switchable operation and relatively high energy pulses. This design may find many applications in different fields, such as laser spectroscopy, biomedical research, and telecommunications system.

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