Tunable all-fiber dissipative-soliton laser with a multimode interference filter

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We report on a tunable all-fiber dissipative-soliton laser with a multimode interference filter that consists of a multimode fiber spliced between two single-mode fibers. By carefully selecting the fiber parameters, a filter with a central wavelength at 1032 nm and a bandwidth of 7.6 nm is constructed and used for spectral filtering in an all-normal-dispersion mode-locked ytterbium-doped fiber laser based on nonlinear polarization evolution. The laser delivers 31 mW of average output power with positively chirped 7 ps pulses. The repetition rate of the pulses is 15.3 MHz, and pulse energy is 2.1 nJ. Tunable dissipative-soliton over 12 nm is achieved by applying tension to the single-mode–multimode–single-mode filter.

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Mode-locked fiber lasers operating at a 1 μm wavelength range have been extensively investigated in recent years owing to their excellent energy performance. Different mode-locking mechanisms, including the stretched-pulse [1] and self-similar methods [2], have promoted the output energy from several nanojoules (nJ) to over 10 nJ. However, a certain degree of dispersion compensation implemented either by bulk grating [3], photonic crystal fiber [4], or high-order mode fiber [5] is necessary to achieve stable mode-locking operation, which results in increased complexity and undermines some of the benefits of fiber lasers. Recently, Chong *et al.* reported stable passively mode-locked all-normal-dispersion fiber laser. The pulse mechanism could be attributed to the strong spectral filtering of the highly chirped dissipative-soliton pulse [6]. However, discrete optical components were used for spectral filtering that destroyed the compactness of the fiber laser.

An all-fiber mode-locked laser without dispersion compensation possesses many advantages, such as excellent compactness, better stability, and easy adjustment. Several fiber bandpass filters were adopted to realize stable mode-locked output. Kieu and Wise demonstrated an all-normal-dispersion mode-locked laser with a CNT-based saturable absorber (SA) and a fused coupler as a filter [7]. Similarly, by using a fused WDM as a filter [8], Schultz *et al.* reported 1.8 nJ highly chirped pulses without dispersion compensation. Özgören and Ilday reported 1 nJ pulses output from an all-fiber all-normal-dispersion laser with a fiber-based Lyot filter [9]. Zhang *et al.* demonstrated a 8.5 nJ dissipative-soliton fiber laser using a commercially available filter, and the pulse could be compressed to 223 fs [10]. Using a HiBi fiber Sagnac loop filter, 20 nm wavelength tuning operation could be achieved by adjusting the polarization controller. However, the spectrum of the laser with a bandwidth of 2.8 nm was not that of the typical dissipative-soliton laser [11].

All fiber single mode–multimode–single mode (SMS) filters based on the multimode interference (MMI) effect have recently attracted significant interest for a range of applications due to easy fabrication, low cost, high compactness, and wide wavelength operation range. It has been employed to make tunable fiber lasers by either lengthening [12] or bending [13] the SMS filter. However, to the best of our knowledge, there are no reports on applying an SMS filter in all-normal-dispersion mode-locked fiber laser to realize a tunable dissipative-soliton operation.

In this Letter, stable dissipative-soliton operation in a dispersion-compensation-free Yb-doped fiber laser based on nonlinear polarization evolution (NPE) was demonstrated by inserting an SMS component to provide the spectral filtering effect. An average output power of 31 mW, corresponding to a pulse energy of 2.1 nJ, was obtained and the pulse width was measured as 7 ps. By stretching the multimode fiber (MMF) of the SMS filter, a tunable dissipative-soliton over 12 nm was achieved.

The SMS filter was fabricated by splicing a piece of MMF between two single-mode fibers (SMFs) [14]. When the light from the input SMF enters the MMF, a number of MMF modes are excited, and the interference between them leads to the self-images of the input light, which allows the light being coupled into the output SMF. The target central wavelength and bandwidth of the SMS filter were chosen to be about 1030 and 8 nm, respectively. For the desired filter, we first conducted a simulation using the method introduced in [15] to determine the parameters of the MMF. The central wavelengths of the transmission peaks are decided by the following equation:

$$\lambda = m\frac{4n_{\mathrm{core}}a^2}{z}, \qquad m = 0, 1, 2\ldots \tag{1}$$

where n_{core} corresponds to the refractive index of the MMF, a represents the radius of the MMF, z represents the length of the MMF, and m is the order of the self-image. From Eq. (1), a series of MMF lengths could be selected to insure the position of the central wavelength. Figure 1(a) shows the bandwidth of the filter as a function of the order of the self-image. A compromise between the desired filter bandwidth and the necessary length of the MMF for the planned experiment on tuning the central wavelength by stretching the fiber, the 12th self image ($m = 12$) is employed, and the corresponding length of MMF is 42 mm. Figure 1(b) demonstrates that the bandwidth of the SMS filter decreases rapidly with the increase of the core diameter of the MMF with the 12th self-image. An MMF with a diameter of 50 μm is therefore chosen in the experiments. The SMF used in fabricating the SMS filter is HI1060.

The transmission spectrum of the fabricated SMS filter was tested with a ytterbium-doped fiber amplified stimulated emission (ASE) source from 1025 to 1100 nm. As shown in Fig. 1(c), the peak wavelength locates at 1032 nm with peak transmission (coupling efficiency) of about 83%, which is less than the simulated result. It may result from the imperfect splices and the eccentricity of the fiber core. The full width at half-maximum (FWHM) bandwidth of 7.6 nm is broader than the simulated bandwidth, which can be explained by the excitation of the high-order azimuthal modes due to a slight misalignment between the SMF and MMF segments [14]. And the simulation considers only radially symmetric modes. By stretching the MMF, the SMS can be tuned. As in [14], the SMS filter was fixed on one end, and the other end was attached to a translation stage. The fiber was fixed at the recoated fusing points between the SMFs and MMF with 2 cm long metal tapes. When adjusting the translation stage, an axial strain was applied to the fiber, which changed the central transmission wavelength of the SMS filter. As shown in Fig. 1(d), the simulated center wavelength of the filter could be tuned by 2.43 nm per 100 micron elongation of the MMF length.

Our laser setup is illustrated in Fig. 2. A piece of 30 cm long highly ytterbium-doped SMF is used as gain medium, which has a nominal core absorption of more than 750 dB/m @976 nm. The pump source is a 500 mW single-mode pigtailed laser diode with a nominal emitting wavelength of 976 nm. Approximately 12% of the beam is

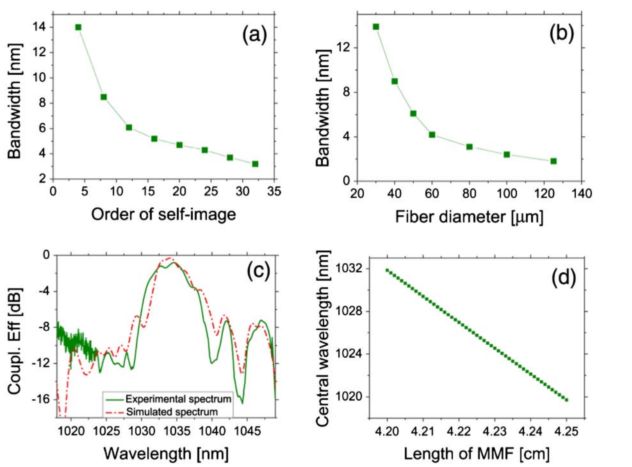

Fig. 1. (Color online) Bandwidth of the filter as a function of (a) the order of the self-image and (b) the diameter of the MMF. (c) Simulated transmission spectrum (dashed–dotted curve) and experimental spectrum (solid curve) of the filter with the 12th self-image. (d) Central wavelength of the filter as a function of the MMF length with the 12th self-image.

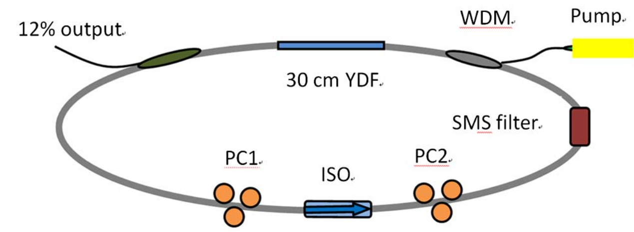

Fig. 2. (Color online) Schematic diagram of the mode-locked fiber laser.

extracted from the cavity through a fiber coupler placed after the gain fiber. Two polarization controllers and a polarization maintaining (PM) isolator function as the NPE mode-locking mechanism. The above-mentioned SMS filter is inserted into the cavity to realize a spectral filtering effect on the highly chirped pulses. The fiber length between the isolator and the SMS filter, between the SMS filter and the gain fiber, and between the gain fiber and the isolator are 3.5, 2, and 7.2 m, respectively. The corresponding overall cavity dispersion is estimated to be 0.31 ps^2 at 1030 nm.

Self-starting mode-locked operation is obtained by adjusting the polarization controllers when the pump power exceeds the threshold. As shown in Fig. 3(a), the mode-locking threshold is about 200 mW, and the output power of 31 mW is achieved at the maximum pump power of 500 mW. The corresponding maximum pulse energy is 2.1 nJ at a pulse repetition rate of 15.3 MHz. Figure 3(b) shows the spectrum of the mode-locked fiber laser, which exhibits a typical characteristic of the dissipative-soliton laser by spectral filtering of the highly

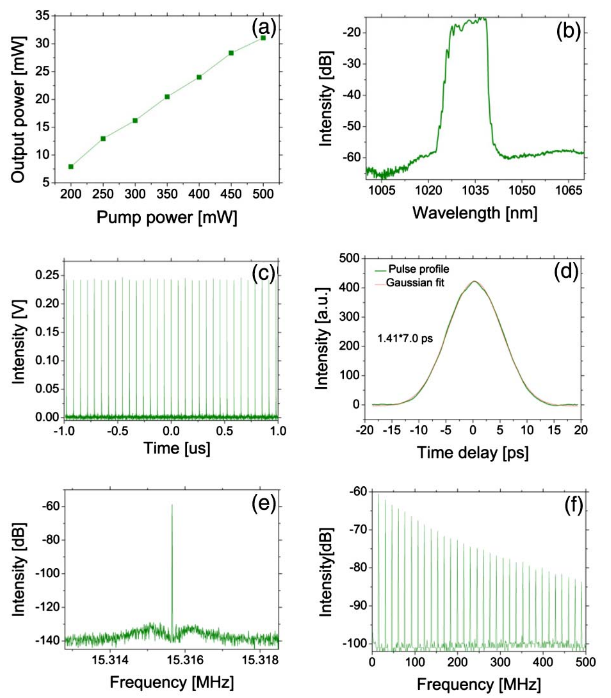

Fig. 3. (Color online) (a) Output power of the mode-locked fiber laser with respect to the pump power. (b) Output spectrum, (c) emitted pulse train, and (d) autocorrelation trace of the mode-locked laser at the maximum output power. The rf spectrum around the (e) fundamental and (f) harmonic repetition rates of the laser.

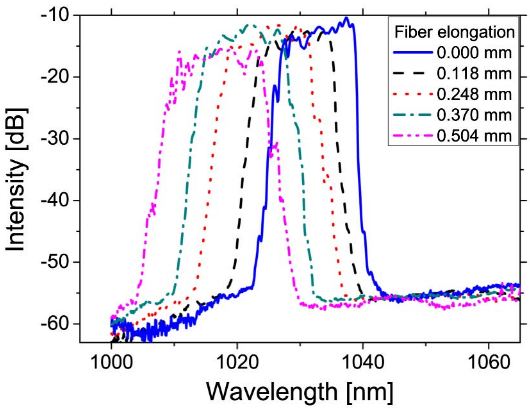

Fig. 4. (Color online) Spectral tuning of the mode-locked fiber laser by applying strain on the SMS filter.

chirped pulse in the all-normal-dispersion regime. Steep sides could be observed at the edges of the spectrum. The central wavelength is about 1032 nm with a 3 dB linewidth of 12 nm. The pulse train measured with a photodiode (1.2 GHz bandwidth) is shown in Fig. 3(c). It exhibits a pulse spacing of 65.36 ns, corresponding to a pulse repetition rate of 15.3 MHz, which matches well with the length of the cavity. The autocorrelation trace of the chirped pulses is measured with a long range autocorrelator (APE SM 1200), and shows a pulse width of 7 ps, as is depicted in Fig. 3(d). The radio frequency (rf) spectra around the fundamental and harmonic repetition rates are shown in Figs. 3(e) and 3(f), respectively, measured with a high resolution rf-spectrum analyzer (Agilent E4405B). The corresponding resolutions are 1 and 100 Hz, respectively. No obvious residual sidebands caused by Q-switched mode-locking could be observed. A 70 dB peak-to-background ratio indicates good mode-locking stability and low pulse timing jitter.

The spectral tuning of the mode-locked fiber laser was implemented by applying strain on the MMF of the SMS filter as described in the previous paragraph. The results are illustrated in Fig. 4. The five spectra shown in the graph correspond to the laser output with a stepwise increase of the MMF length, up to 0.504 mm elongation. Up to 12 nm tuning range was achieved accordingly, which matches the simulation well. Note the mode-locking could not be preserved during the wavelength tuning, because the polarization evolution in the fiber is wavelength dependent. Moreover, the continuous tuning could be influenced by the interplay between the tunable SMS filter and the intrinsic Lyot filter that is always present in such a cavity [13,16]. Stable dissipative soliton operation was achieved at each situation by re-adjusting the PCs. No significant changes of the output power and pulse width at different output wavelengths were observed.

In conclusion, we have demonstrated all-fiber tunable dissipative-soliton operation in an all-normal-dispersion Yb-doped fiber laser using an SMS filter. An SMS filter with a peak wavelength of 1032 nm and bandwidth of 7.6 nm was fabricated. The laser delivered 31 mW of average output power with positively chirped 7 ps pulses. The repetition rate of the pulses is 15.3 MHz, and pulse energy is 2.1 nJ. A tunable dissipative-soliton laser over 12 nm was achieved by stretching the MMF of the SMS filter. The SMS filter is an all-fiber device and easy to fabricate. We believe the reported laser configuration is an attractive, low cost, and accessible solution for generating wavelength-tunable all-normal-dispersion mode-locked fiber lasers, and can find wide applications in second harmonic generation, material processing, microscopy, and imaging.

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