All-Polarization-Maintaining Tunable Mode-Locked Er-Doped Fiber Laser with a Compact Reflective Lyot Filter

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***Abstract*—An all-polarization-maintaining tunable carbon nanotube mode-locked Er:fiber laser is demonstrated based on a compact reflective Lyot filter, with wavelength tuning slope of 0.62 nm/°C, 47.7 times higher than that of fiber grating based tunable lasers.**

Keywords—mode-locked fiber lasers, carbon nanotubes, tunable fiber lasers, Lyot filter

I. INTRODUCTION

Mode-locked lasers are promising for various applications such as ultrahigh-resolution spectroscopy[1], high-efficient materials processing[2], ultrafast communication[3], biomedical imaging[4, 5], and also serve as an excellent platform for ultrafast science and nonlinear research[6]. Fiber based mode-locked lasers show special potential for their compact size, low cost, high stability, and perfect thermo-management.

To meet the wavelength requirement for different applications, wavelength-tunable mode-locked fiber lasers are developed. Typically, the pulse wavelength can be tuned by rotating the grating[7, 8], adjusting the free-space bandpass filter in free space optics[9]. Compared to adjusting the free space components, optical fiber based filters are more promising for making all-fiber tunable mode-locked lasers, with calibration-free, compactness and robustness. Optical fiber filters for tuning the wavelength can be divided into transmissive type and reflective type. In transmissive filters, fiber grating is the frequently-used one owing to its compact size, however, its low-temperature sensitivity make it difficult to tune the wavelength in a wide range[10, 11]. Polarization maintaining (PM) fiber based Sganac loop is also widely adopted to realize wide wavelength tuning owing to the high thermo-optic coefficient of PM fiber[12, 13]. However, the loop mirror can hardly be accepted to achieve a higher repetition rate. For the transmissive type filters, the PM fiber based Lyot filter is widely used combining the wide tuning range and straightforward operation[14].

In this paper, we propose and demonstrate a compact reflective Lyot filter with high temperature sensitivity. The temperature-dependent wavelength tuning ability of the filter is experimentally proved. Furthermore, based on this device, we demonstrate a tunable carbon nanotube (CNT) mode-locked Er:fiber laser with all-PM fiber configuration. The experiment results show that the output central wavelength can be thermally tuned in a wide range of 18.51 nm, with the tuning slope of 0.62 nm/°C. This kind of compact filter is promising for wavelength tuning in mode-locked fiber laser cavities, especially in linear cavities.

II. EXPERIMENT RESULTS AND DISCUSSIONS

The proposed reflective Lyot filter is shown in Fig. 1. The filter consists of a PM circulator with only slow axis working, a section of PM fiber and a fiber ferrule mirror. The PM fiber is fusion spliced with the pigtail PM fiber of the circulator with an angle of 45°. When the light is launched, the light only propagates in the slow axis. The 45-degree splice splits the light into two orthogonal modes and recouple them to have a birefringence interference, which is the principle of the reflective Lyot filter.

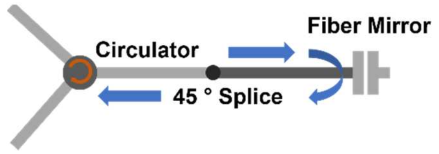

Fig. 1. Schematic diagram of the reflective Lyot filter.

We fabricated the filter with different interference lengths (twice the length of the angle-spliced PM fiber) to check the reflection spectra of the filter. The light was launched from a broadband light source (Amonics, AEDFA-PM-23-B-FA), and the reflection spectra were recorded by an optical spectrum analyzer (OSA, Yokogawa 6375D). The experiment results are shown in Fig. 2. The reflection spectra of the filter with the angle-spliced PM fiber length of 46.5 cm, 30.5 cm, 17.5 cm, 12 cm, and 9.7 cm, were recorded in (a), (b), (c), (d) and (e), respectively. From the figure, we can clearly observe that the free spectral range (FSR) of the filter increases with the decrease of the fiber length. The FSRs are 5.59 nm, 8.64 nm, 14.37 nm, 20.84 nm and 25.51 nm, corresponding to 5 fiber lengths. Meanwhile, as the fiber length becomes shorter, the interference extinction ratio remains high, which is benefiting from the excellent birefringence interference of two orthogonal modes. When the filter is used for wavelength tuning in fiber lasers, the tuning range could be well controlled by carefully choosing the fiber length.

Next, we carried out the temperature experiment to get the temperature response coefficient and obtain the interference curve location as a reference for laser wavelength tuning. From our previous works, the larger FSR of the filter can help to get a broader wavelength tuning range. Therefore, the filter with FSR of 25.51 nm was chosen for the temperature experiment. The spectral evolution of the filter and the wavelength shift of the interference dips were recorded in Fig. 3 and Fig. 4, respectively.

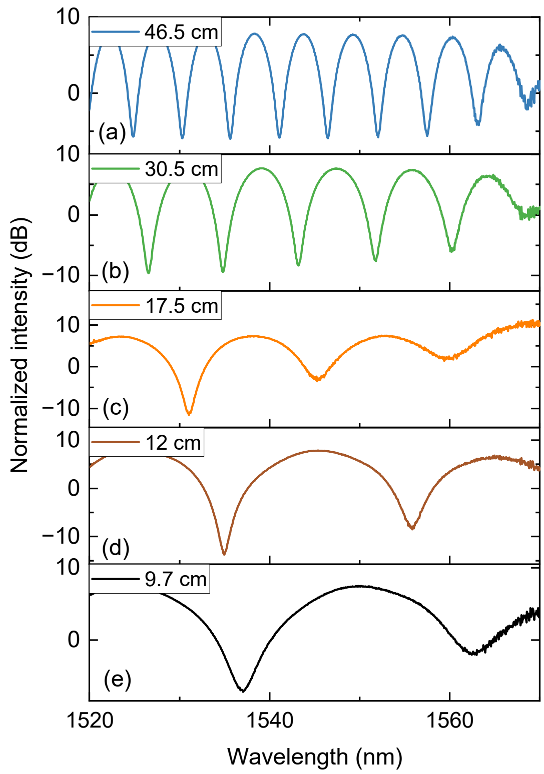

Fig. 2. Reflection spectra of the filter with the angle-spliced fiber lengths of (a)46.5 cm, (b)30.5 cm, (c)17.5 cm, (d)12 cm and (e)9.7 cm, respectively.

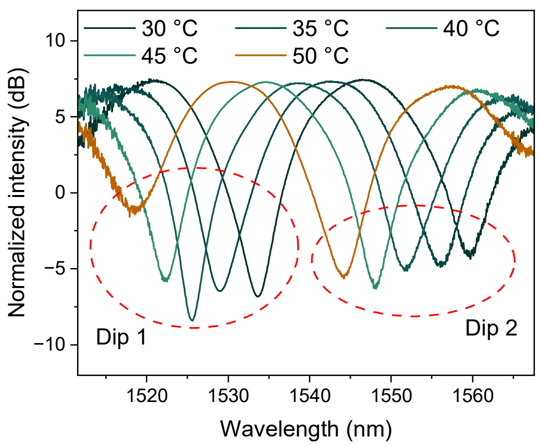

Fig. 3. The reflection spectra of the filter with 9.7-cm angle-spliced fiber under different temperatures.

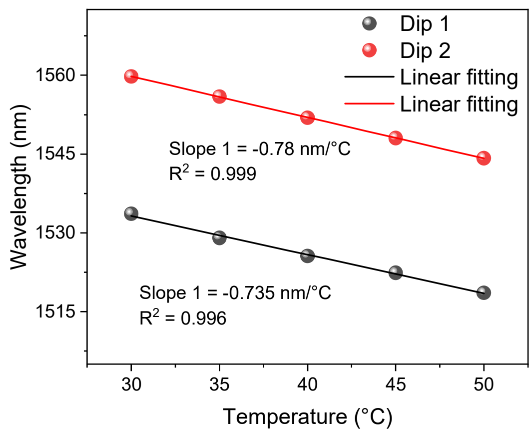

Fig. 4. Wavelength shifts and linear fittings of two interference dips.

When we set the temperature as 30 °C, two interference dips of the filter were clearly located within the wavelength window. Therefore, 30 °C was set as the start temperature. Then, the temperature was increased by step of 5 °C, the corresponding spectra were recorded. We can obverse from Fig. 3 that, when the temperature was increased from 30 °C to 50 °C, the interference dips (1 and 2) were uniformly blue-shifted. When the temperature was set as 50 °C, the dip 1 reached the margin of the wavelength window. The detailed wavelength shift is shown in Fig. 4. For dip 1, the wavelength is shifted from 1533.7 nm to 1518.4 nm, with a slope of -0.735 nm/°C. And for dip 2, the wavelength is shifted from 1559.7 nm to 1544.3 nm, with a slope of -0.78 nm/°C. The R^2 of two linear fitting curves are above 0.99, shows excellent linear relationship between the dip wavelength shift and temperature change.

To evaluate the wavelength tunability of the Lyot filter in mode-locked fiber laser system, we built up a standard all-PM ring-cavity laser oscillator with the proposed filter, which is shown in Fig. 5. The laser cavity contains a PM tap isolating wavelength-division multiplexing (TIWDM) coupler, which integrates the functions of a wavelength-division multiplexer (WDM), an isolator, and a 50% output coupler. 80-cm PM Erbium-doped fiber (EDF, Nufern PM-ESF-7/125) is used as the gain medium. The CNT saturable absorber (CNT-SA), prepared by the spray method, makes the laser mode-locked. The pump is a 980-nm laser diode (LD). The proposed Lyot filter is connected to the cavity by the circulator. In this laser cavity, all the components and fibers are PM type.

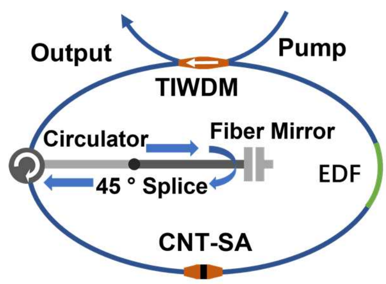

Fig. 5. Experiment setup of the all-PM mode-locked fiber laser.

Under the room temperature, the laser mode-locking was self-started when the pump power reaches ~40 mW. Once the laser is locked, the optical spectra in both logarithmic and linear scales were measured by abovementioned OSA. As seen in the Fig. 6, the central wavelength λ_c of the output laser is located at 1556.4 nm, and the full width at half maximum (FWHM) is 2.07 nm. Owing to the anomalous net cavity dispersion, the optical pulse is traditional soliton.

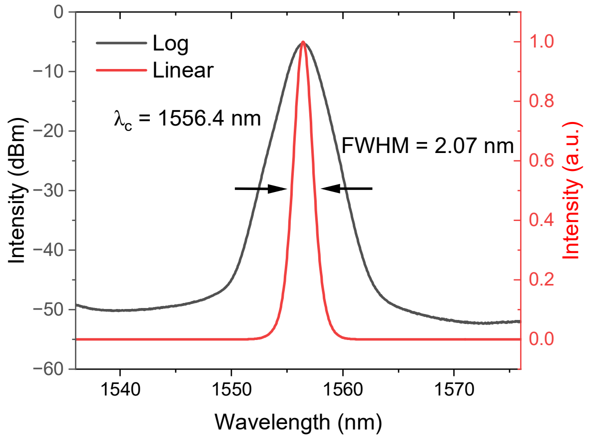

Fig. 6. The optical spectra of the mode-locked fiber laser in both logarithmic and linear scales.

The pulse train was measured and analyzed by a photodetector (NEW FOCUS, IR 1GHz) and an oscilloscope (RIGOL, DS2202E), which is shown in Fig. 7. There was a clear and stable single pulse train displayed on the oscilloscope. The measured pulse interval is 46 ns, the corresponding repetition rate and cavity length are 21.7 MHz and 9.5 m, respectively. The results are well consistent to the experiment setups.

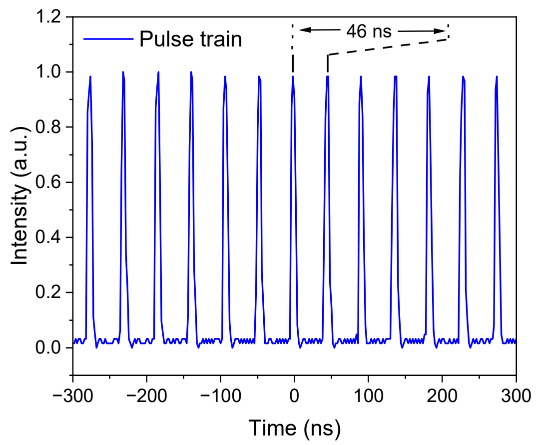

Fig. 7. Pulse train of the laser output.

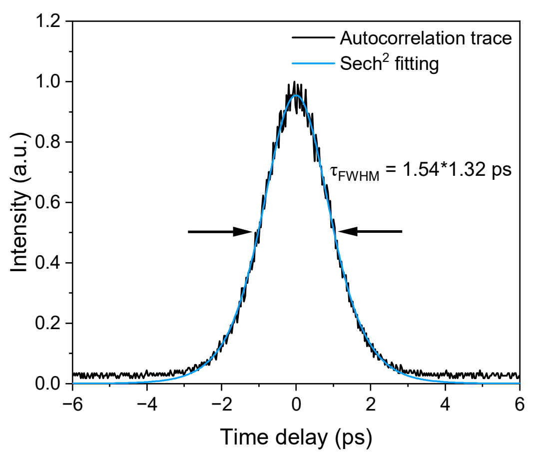

Fig. 8. Autocorrelation trace and sech^2 fitting of the laser pulse.

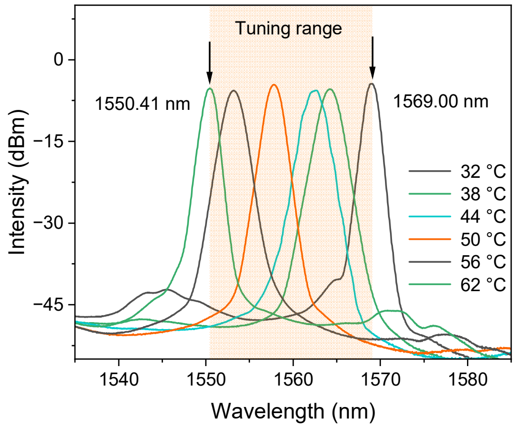

Fig. 9. Wavelength tuning of the mode-locked fiber laser.

The autocorrelation trace and its sech^2 fitting curves of the laser pulse are shown in Fig. 8. The measured FWHM pulse width is 2.04 ps (1.54×1.32 ps) when the sech^2 fitting is applied, and the time-bandwidth product (TBP) is calculated as 0.338, which is very close to 0.315, the idea TBP of sech^2 pulses .The slight difference between the two are supposed to be caused by the single mode fiber outside the cavity when measuring the pulse width. The above experiment results show that the stable mode-locking can be achieved in the proposed all-PM laser cavity with CNT-SA and reflective Lyot filter.

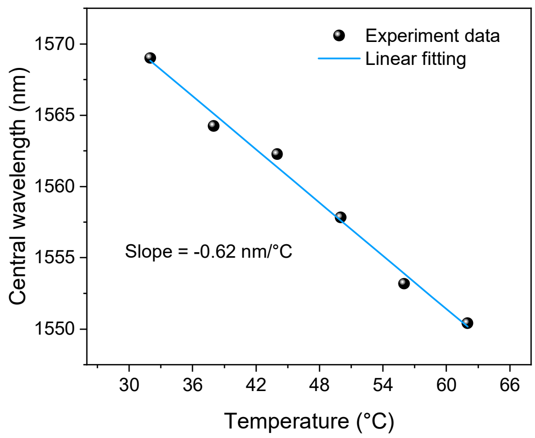

Fig. 10. Relationship between the laser central wavelength and the temperature.

To verify the laser wavelength tunability of the proposed Lyot filter, the temperature tuning experiment was carried out. We increased the temperature controller from room temperature to find the tuning boundary. When the temperature was set as 32 °C, the mode locked pulse was rebuilt up at the central wavelength of 1569 nm. Then, the temperature was uniformly increased by step of 6 °C. In each temperature, the optical spectra were recorded. When the temperature was set as 62 °C, the central wavelength was located at 1550.41 nm. When the temperature was further adjusted, the mode-locking state at this wavelength was broken, and the pulse at near 1569 nm was rebuilt up. Therefore, the wavelength of 1550.41 nm was regarded as the left boundary of the wavelength tuning. Therefore, the laser wavelength can be tuned from 1569 nm to 1550.41 nm, with a tuning range of 18.59 nm. The central wavelength changes under temperature variations are plotted in Fig. 10, linear fitting is employed to depict their relationship. The tuning slope is calculated as -0.62 nm/°C, which is a litter lower than the sensitivity of our previous temperature experiment on the sole Lyot filter. This may result from the different heating lengths and positions of the two experiments. Even so, the wavelength tunability is 47.7 times higher than the fiber grating based tunable lasers[15].

III. Conclusion

To conclude, in this paper, a compact reflective Lyot filter with good thermal sensitivity is proposed. The temperature sensitivities of two different interference dips are measured as -0.735 nm/°C and -0.78 nm/°C, respectively. Based on the reflective Lyot filter with a FSR of 25 nm, an all-PM tunable CNT mode-locked Er:fiber laser is realized with the wavelength tuning range of ~18.51 nm. The proposed reflective Lyot filter is promising for compact wavelength tunable mode-locked fiber lasers, especially linear cavity lasers.

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