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RESEARCH ARTICLE

Bidirectional Single Longitudinal Mode Er-Doped Fiber Ring Laser Using a Bandpass Filter and Cascaded Fiber Ring Filter

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ABSTRACT Bidirectional single longitudinal mode fiber ring laser have advantages and potential in optical sensing, especially angular velocity sensing. The current methods for implementing bidirectional single longitudinal mode fiber ring laser cannot ensure complete reciprocity in the optical path, and the side mode suppression ratio needs to be increased, while the laser linewidth is relatively wide. This paper proposes a combined filtering structure using a bandpass filter and a cascaded add-drop type fiber ring filter. When realizing bidirectional single longitudinal mode output, the optical path structure is fully reciprocal including polarization state reciprocity, while the side mode suppression ratio is relatively high. The linewidth of the bidirectional laser is around 1.1 kHz, far lower than the previous report of tens of kHz. The fully reciprocal combined filter structure proposed in this paper does not require special devices, and its theoretical system is mature, which is conducive to the subsequent application and improvement of bidirectional single longitudinal mode fiber ring laser.

INDEX TERMS Bidirectional Er-doped fiber ring laser, compound-cavity, fiber ring filter, single longitudinal mode.

I. INTRODUCTION

Fiber optic laser sensors have potential advantages over traditional fiber optic interferometric sensors in terms of fiber optic configuration and electronic signal processing [1], [2], [3]. Bidirectional fiber ring laser also has the same advantages in angular velocity sensing, the fiber optic ring laser gyroscope built from rare earth doped fiber is the easiest to implement [4]. The ring laser gyroscope has the most stable performance when the output laser light in both clockwise(CW) and counterclockwise(CCW) directions is a single longitudinal mode laser [5].

Three main methods exist for realizing single longitudinal mode output in existing bidirectional ring cavity fiber lasers. The first method introduces nonreciprocal effects or structures into the optical path, mainly to solve the multiple longitudinal mode output caused by the spatial hole burning effect in the gain medium and to avoid the mode-locking phenomenon [5]. There are three main ways, the first is to add a Faraday rotator to introduce a nonreciprocal phase difference in the CW and CCW transmission light, which causes a certain difference in the CW and CCW laser frequencies, thereby preventing interference, avoiding the formation of gain gratings in the gain medium, and achieving single longitudinal mode output [5], [6]. The disadvantage is that the angle of the Faraday rotator is unstable, and changes in intracavity birefringence can affect the stability of the beat signal. The FSR of the fiber ring filter used in the system is not wide enough, resulting in poor single longitudinal mode stability. The second way is to eliminate the spatial hole burning effect by combining a Faraday optical rotator with polarizers so that the polarization states of CW and CCW transmission light are perpendicular to each other and cannot form interference [7], [8]. This way cannot achieve absolute perpendicularity between CW and CCW lights, and there is still interference between the two light directions. At the

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same time, both the mode selection device and the Mach Zender filter in the optical path are nonreciprocal devices. Significant polarization state disturbances in the cavity also lead to large jitter in the beat signal. Literature [9] uses PBS to make the polarization of different propagation directions vertical to avoid spatial hole burning. However, CW and CCW polarization is still not reciprocal. Literature [10] uses polarization-maintaining fiber to replace part of single-mode fiber while using a 90° fusion method to increase reciprocity. However, it cannot fully overcome the impact of polarization disturbances in principle. The third way is to use quarter wave plates plus a polarizer structure so that the polarization state of CW and CCW transmission light is in a circularly polarized state and also cannot form an interference standing wave to eliminate the spatial hole burning effect to achieve a single longitudinal mode [11]. This way is difficult to maintain the circularly polarized transmission during the propagation process thoroughly, and there is nonreciprocal interference between the CW and CCW output lights.

The second method uses narrow band gratings formed in saturable absorber to obtain bidirectional single longitudinal mode output [12]. This method uses two sets of FBGs plus unpumped erbium-doped fibers to filter CW and CCW transmitted light through a nonreciprocal optical path structure to obtain bidirectional single longitudinal mode operation. However, due to the nonreciprocity of the optical path, the CW and CCW resonant frequencies of this method are different. This method obtained the current narrowest linewidth of a bidirectional single longitudinal mode fiber ring laser at 47 kHz.

The third method is a compound cavity filtering method, which obtains a single longitudinal mode output through the vernier effect between the primary ring resonator FSR and the sub ring resonator FSR. The literature [13], [14] selects a suitable length difference between the primary and sub resonators. A large FSR is obtained through the vernier effect, achieving bidirectional single longitudinal mode output. However, this method requires a length difference of several millimeters between two resonators, making it difficult for the optical fiber fusion process. Both the primary and sub resonators use gain optical fibers, which is costly. Moreover, when the resonator length difference is slight, the side mode suppression ratio of the filter is also poor, so it is necessary to consider a better filter structure and combination method.

Fiber ring filters have been widely used in unidirectional fiber ring lasers [15], [16], [17], [18], [19], [20], [21]. Fiber ring filters are mainly made of standard optical fiber couplers, with convenient material acquisition and low cost. There is a mature theoretical system that can guide the specific parameter design of experiments, and the theoretical foundation is relatively complete. It is generally impossible to achieve single longitudinal mode output by relying solely on a single fiber ring filter. Usually, single longitudinal mode output is achieved through the vernier effect of two cascaded fiber ring filters [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. However, relying only on cascaded fiber ring filters to filter out a single longitudinal mode in an erbium-doped fiber laser, the length difference between the two fiber ring filters is slight. At this time, the filtering effect of the filter, such as the suppression of side modes, is poor, which is not conducive to long-term stable output and high power output [34]. Moreover, when the length difference of the fiber optic loop filter is slight, it will be more susceptible to external environmental disturbances, such as temperature changes, which are not conducive to the system's overall stability. Therefore, it is necessary to consider the combination of cascaded fiber ring filters and other filters. Thin film filters are single bandpass filters with a wide bandwidth, while Fabry-Perot filters are comb-shaped spectral filters but can achieve a smaller bandwidth. Therefore, a combination of Fabry-Perot filters and a bandpass filter can achieve a narrow band single bandpass filter. Cascaded fiber ring filters based on bandpass filters can achieve a better filtering effect.

This paper proposes a bidirectional fully reciprocal combined filter structure based on bandpass filter and cascaded fiber ring filters. The initial filtering of the system through a bandpass filter can significantly reduce the number of optical modes in the system. On this basis, a cascaded add-drop type fiber ring filter is combined to obtain a single longitudinal mode output. Thereby reducing the requirements for cascaded fiber ring filters FSR, improving the side modes suppression ability of cascaded fiber ring filters, and using fiber ring filter to narrow the linewidth of bidirectional lasers. All optical path structures use PM fibers, and the polarization state of CW and CCW transmission light is entirely reciprocal, avoiding interference from polarization state disturbances on the system.

II. EXPERIMENTAL SETUP AND PRINCIPLES

A. PRINCIPLE OF FIBER RING FILTER

Fiber ring filters mainly have two configurations: all-pass and add-drop. All-pass fiber ring filter has a low suppression ratio for side modes at high pump power. A fiber ring filter with an add-drop configuration has a higher side mode suppression ratio when cascaded, so the fiber loop filter with an add-drop configuration is selected.

A typical add-drop type fiber ring filter is shown in Fig. 1, which is formed by fusing two optical couplers. When selecting the lower left corner as the input port, the upper left corner is the drop port, the upper right corner is the add port, and the lower right corner is the through port.

The transmission equation of the optical coupler is:

$$\begin{bmatrix} E_t \\ E_2 \end{bmatrix} = \begin{bmatrix} t_1 & -ik_1 \\ -ik_1 & t_1 \end{bmatrix} \begin{bmatrix} E_i \\ E_1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} E_d \\ E_4 \end{bmatrix} = \begin{bmatrix} t_2 & -ik_2 \\ -ik_2 & t_2 \end{bmatrix} \begin{bmatrix} E_a \\ E_3 \end{bmatrix} \tag{2}$$

The transmission equation in the optical fiber ring is:

$$E_3 = a_1 e^{-j\theta_1} E_2 \tag{3}$$

$$E_1 = a_2 e^{-j\theta_2} E_4 \tag{4}$$

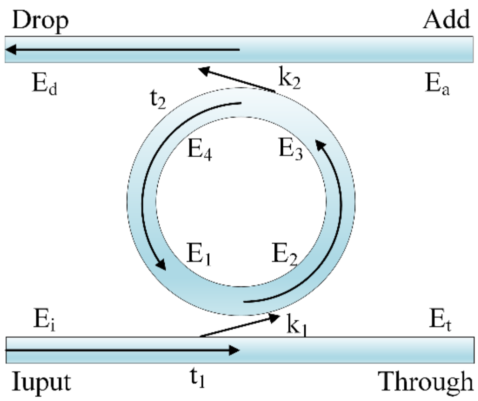

FIGURE 1. **Structure diagram of add-drop type fiber ring filter.**

In the formula, t and k are the coupling coefficients of the coupler, a_1 and a_2 are the transmission loss coefficients on the right and left sides of the fiber ring, respectively. θ_1 and θ_2 are the phase change amounts on the fiber ring's right and left sides, respectively. The output relationship of each port can be obtained by combining the optical coupler's transmission equation and the fiber ring's transmission equation. The expression for the transmittance of the drop port and the through port relative to the input port is:

$$\left|\frac{E_d}{E_i}\right|^2 = \frac{a_1^2 k_1^2 k_2^2}{1 - 2a_1 a_2 t_1 t_2 \cos(\theta_1 + \theta_2) + a_1^2 a_2^2 t_1^2 t_2^2} \quad (5)$$

$$\left|\frac{E_t}{E_i}\right|^2 = \frac{t_1^2 - 2a_1 a_2 t_1 t_2 \cos(\theta_1 + \theta_2) + a_1^2 a_2^2 t_2^2}{1 - 2a_1 a_2 t_1 t_2 \cos(\theta_1 + \theta_2) + a_1^2 a_2^2 t_1^2 t_2^2} \quad (6)$$

According to the above equations, simulating the transmission spectrum of the drop and through ports. Considering the reciprocity of bidirectional operation, the coupling ratios of the two couplers should be equal. Due to the limitations of the fiber fusion process, the ring length of a single fiber ring filter must be manageable, and the FSR of the comb spectrum filter formed is insufficient to filter out a single longitudinal mode directly. Therefore, two fiber ring filters with length differences are used to obtain a larger FSR through the vernier effect, thereby filtering out a single longitudinal mode.

When using two fiber ring filters with length differences, the evaluation of filtering effectiveness mainly includes three indicators: FSR after cascading, transmittance, and side mode suppression ratio (Here, side mode suppression ratio is defined as the ratio of the height of the central peak to the height of the first side-peak.). The filtering effectiveness is related to the length difference of the two fiber ring filters, the coupler coupling ratio, and the transmission loss coefficient in the ring.

According to the simulation results, the side mode suppression effect is poor when the length difference between two fiber ring filters is slight. The filter will also be more sensitive to external disturbances. Therefore, two fiber ring filters need a sufficient length difference while selecting a reasonable coupling ratio to achieve better filtering results.

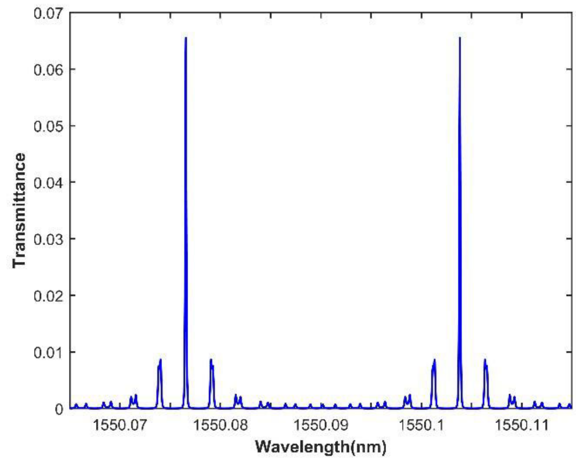

FIGURE 2. **Output transmission spectrum of cascaded add-drop fiber ring filter.**

Better side mode suppression effects can be achieved when the length difference between two fiber ring filters is more than 6 cm. Considering the optical fiber fusion process level, the optical fiber ring filter length is selected to be 60 cm and 66 cm, respectively, and the coupler coupling ratio is 90:10 ($t^2 = 0.9$), transmission loss coefficients a_1 and a_2 are 0.95. As shown in Fig. 2, the FSR of the cascaded fiber ring filter is about 3.4 GHz with a side mode suppression ratio of about 7.

B. PRINCIPLE OF COMBINED FILTERING

Generally, the FSR of a comb spectrum filter should be 0.5-1 times of the bandwidth of a bandpass filter [24]. Therefore, the bandwidth of the bandpass filter should be 3.4-6.8 GHz at this time.

Ordinary bidirectional optical filters include thin film, M-Z, and F-P filters. Considering the bidirectional optical path reciprocity requirements, M-Z filters are first excluded. The bandwidth of the thin film filter is around 50 GHz, which cannot meet the system requirements. Using an FP filter with an FSR of 50GHz and a 3dB bandwidth of 5GHz. The thin film filter combines with F-P filter to ensure that a 5GHz bandpass filter with a single passband can be formed when there is only one F-P filter transmission peak within the thin film filter bandwidth, meeting system requirements.

The main loop length of the system is about 17m, the FSR is about 12MHz, and the FWHM of the passband after cascading two fiber ring filters is about 14.1MHz, which also meets the requirements.

Fig. 3 shows the process of obtaining a single longitudinal mode output. There is a certain difference in the FSR of the two fiber ring filters. The FSR of the cascaded fiber ring filter is 3.4 GHz, and then the single longitudinal mode output is obtained through a bandpass filter.

The optical path structure used in the experiment is shown in Fig. 4. An EDFA provides the system gain without an isolator and is internally pumped by a 980 nm laser. Introduce the laser in both directions through two 90:10 couplers, and

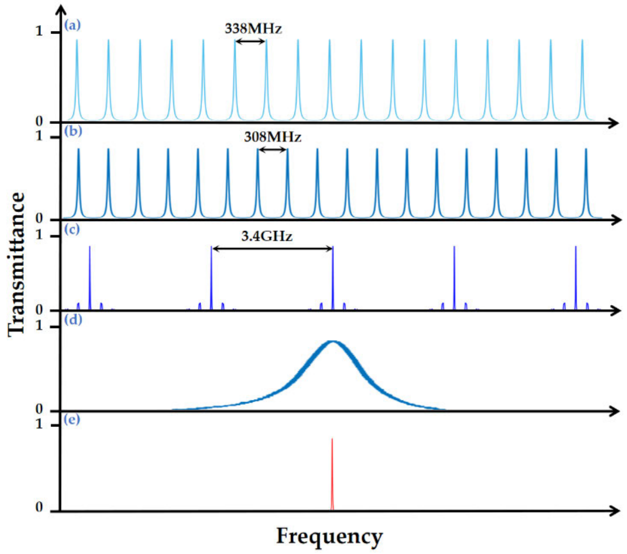

FIGURE 3. Schematic diagram of obtaining single longitudinal mode output: (a) simulation transmission spectrum of fiber ring filter 1; (b) simulation transmission spectrum of fiber ring filter 2; (c) simulation transmission spectrum of cascaded fiber ring filter; (d) simulation transmission spectrum of bandpass filter; (e) simulation single longitudinal mode output.

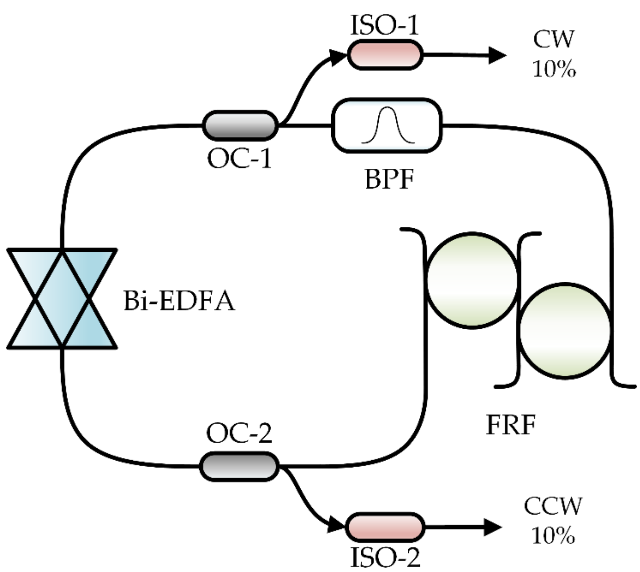

FIGURE 4. Structure diagram of bidirectional fiber ring laser.

add isolators to prevent the impact of reflected light on the operation of the resonant cavity. The system uses a combination filter, a single passband bandpass filter composed of an F-P filter and a thin film filter is used, as well as a cascaded add-drop type fiber ring filter.

III. RESULTS

A. FIBER RING FILTER TEST

In the experiment, a swept light source was used to detect the transmission spectrum to obtain filtering parameters for

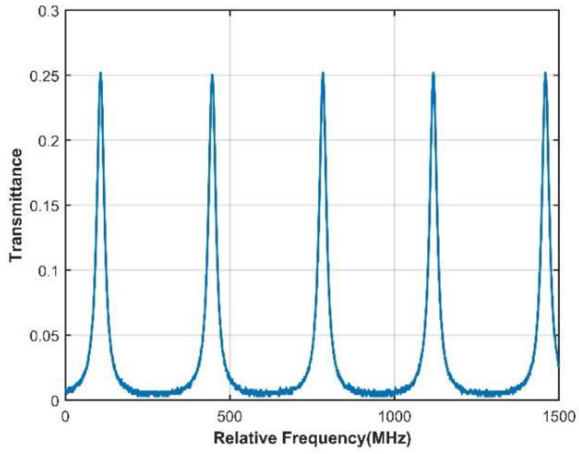

FIGURE 5. Output transmission spectrum of add-drop fiber ring filter 1.

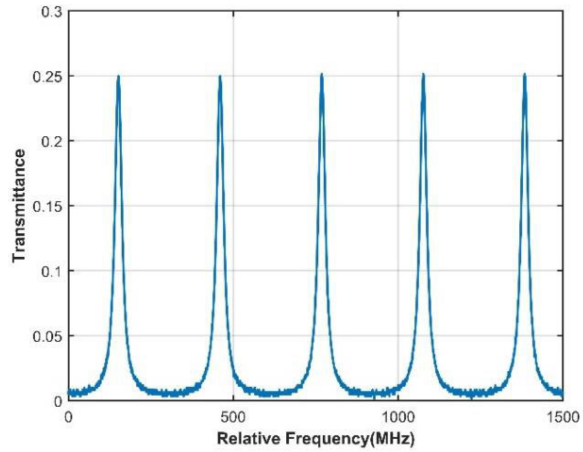

FIGURE 6. Output transmission spectrum of add-drop fiber ring filter 2.

various filters. Fig. 5 shows the transmission spectrum of fiber ring filter 1, with an FSR of 337.66 MHz and a corresponding ring length of 60.85 cm. The FWHM of the passband is about 24.2 MHz, and the maximum transmittance is about 0.25.

Fig. 6 shows the transmission spectrum of fiber ring filter 2, with an FSR of 307.69 MHz and a corresponding ring length of 66.78 cm. The FWHM of the passband is about 22.1 MHz, and the maximum transmittance is about 0.25.

Fig. 7 shows the transmission spectrum of fiber ring filter 1 cascaded with 2, with an FSR of 3.37 GHz. The FWHM of the passband is about 15.6 MHz, the side mode suppression ratio is about 7, and the maximum transmittance is about 0.06.

B. BAND PASS FILTER TEST

The transmission spectrum of the thin film filter is tested as shown in Fig. 8, with a 3dB bandwidth of about 50.2GHz and a maximum transmittance of about 0.8.

Test the transmission spectrum of the F-P filter as shown in Fig. 9. The FSR is about 49.8 GHz, the 3dB bandwidth is about 5.5 GHz, and the maximum transmittance is about 0.83.

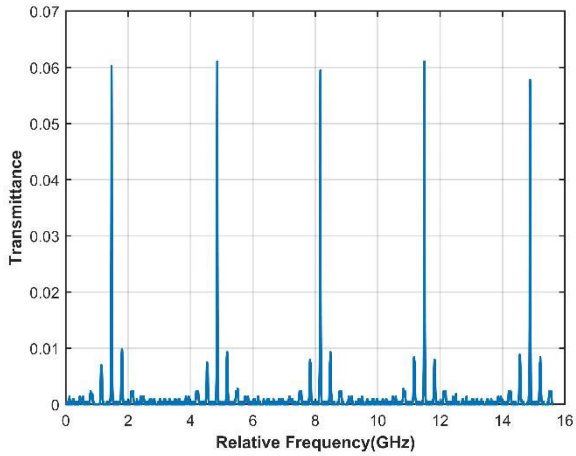

FIGURE 7. Output transmission spectrum of add-drop fiber ring filter 1 combined with 2.

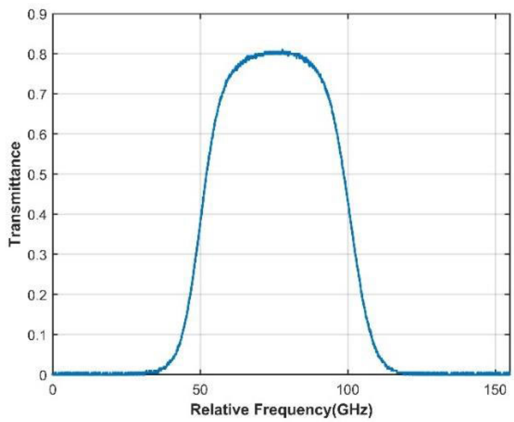

FIGURE 8. Output transmission spectrum of thin-film filter.

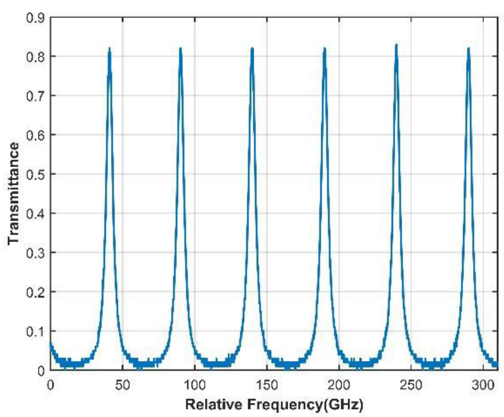

FIGURE 9. Output transmission spectrum of F-P filter.

The combined filtering effect of the thin film filter and F-P filter was tested as shown in Fig. 10, with a 3dB bandwidth of about 5.5 GHz and a transmittance of about 0.65.

Test the filtering effect of the combination of a bandpass filter and a cascaded fiber ring filter. There is only one main peak within the range of the bandpass filter as shown in Fig. 11. The main peak passband FWHM is about 15.5 MHz, the side mode rejection ratio is about 7, and the transmission ratio is about 0.038.

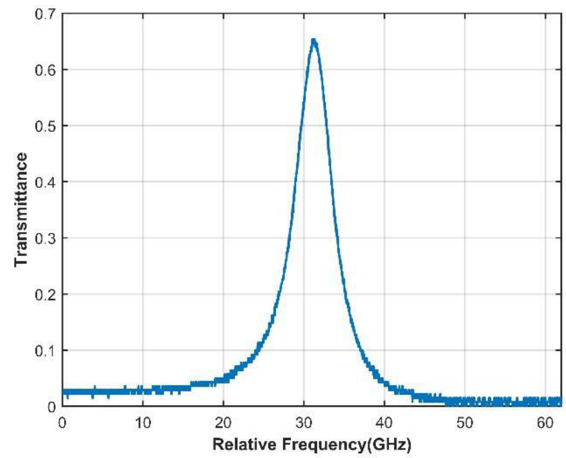

FIGURE 10. Output transmission spectrum of thin-film filter combined with F-P filter.

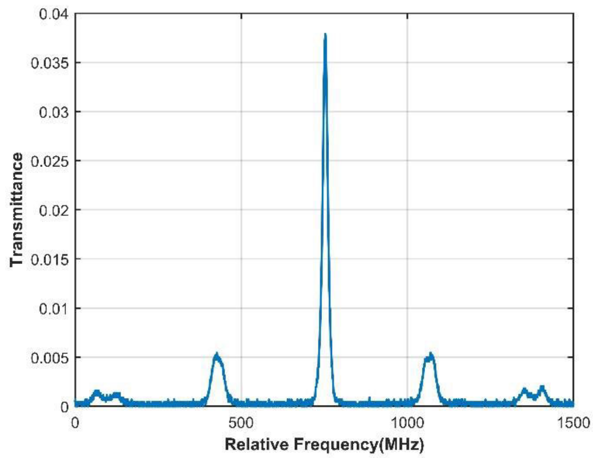

FIGURE 11. The final output transmission spectrum of the combined filter.

C. SINGLE LONGITUDINAL MODE EXPERIMENT

When only a bandpass filter is added to the optical path and no fiber ring filter is added, the measured frequency spectrum of the laser is shown in Fig. 12.

In the case of the only bandpass filter, there are many longitudinal modes, with a longitudinal mode FSR of about 17 MHz and the corresponding system main ring length of 12 m. After adding a fiber ring filter, the corresponding FSR of the fiber ring filter is about 308MHz, and the longitudinal modes except for 308MHz and its multiples are well suppressed as shown in Fig. 13.

After adding a cascaded fiber ring filter, there are no other longitudinal modes in the CW (Fig. 14) and CCW (Fig. 15) directions, and both operate in a single longitudinal mode state.

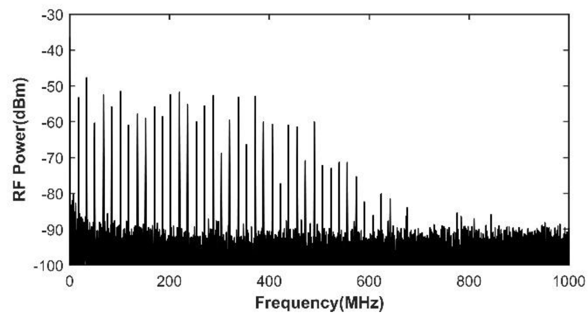

FIGURE 12. Measured frequency spectrum of the laser output without fiber ring filter in 1 GHz span.

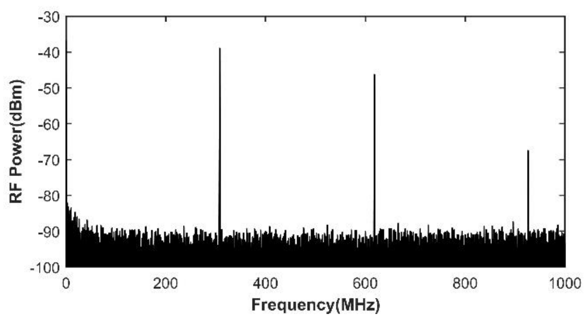

FIGURE 13. Measured frequency spectrum of the laser output when adding a fiber ring filter in 1 GHz span.

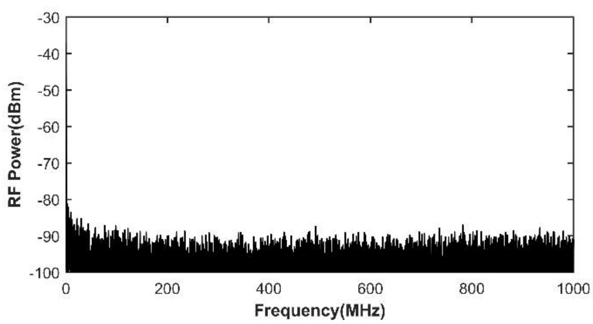

FIGURE 14. Measured frequency spectrum of the CW laser output when adding cascaded fiber ring filter in 1 GHz span.

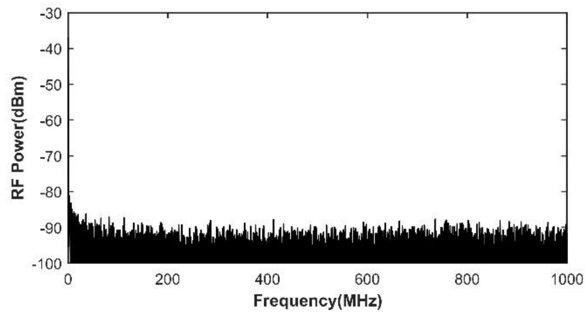

FIGURE 15. Measured frequency spectrum of the CCW laser output when adding cascaded fiber ring filter in 1 GHz span.

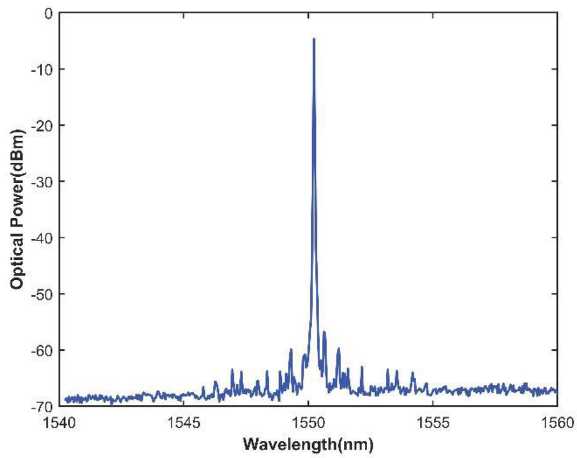

FIGURE 16. Spectrometer result of CW laser.

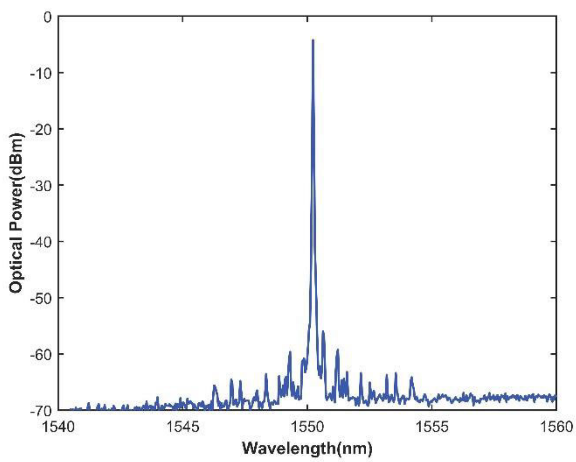

FIGURE 17. Spectrometer result of CCW laser.

Observe the CW and CCW output laser through a spectrometer, and there is only one peak on the spectrometer. The optical signal-to-noise ratio of the CW (Fig. 16) and CCW (Fig. 17) laser is about 55dB. The spectrometer has a resolution of 0.03nm, and no significant wavelength jitter was observed on the spectrometer.

The linewidth of the laser was measured using a delayed self-heterodyne optical path, and the length of the SMF delay line used was 20 km. The linewidths of the CW (Fig. 18) and CCW (Fig. 19) lasers obtained by fitting the results were close to 1.1 kHz.

By comparing with other schemes, the scheme using cascaded add-drop fiber ring filter has achieved the narrowest output linewidth. The specific parameter comparison is listed in Table 1.

There is gain competition in bidirectional fiber lasers, and the CW and CCW optical power are not equal. How to stabilize and balance bidirectional power is a topic worth further research. At the same time, the thin film filter and FP filter used in the scheme has temperature adjustable characteristics,

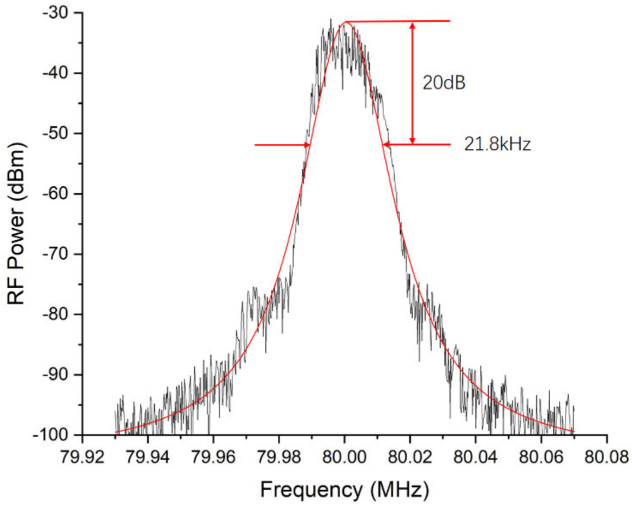

FIGURE 18. Delayed self-heterodyne RF beating spectra of CW laser, adjusted R-Square is 0.9762.

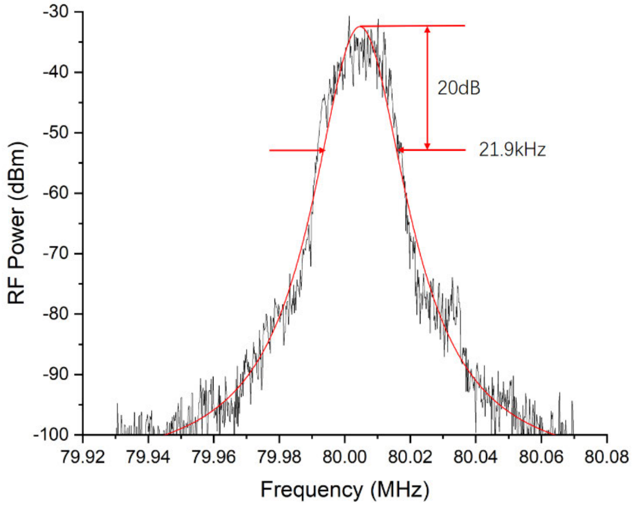

FIGURE 19. Delayed self-heterodyne RF beating spectra of CCW laser, adjusted R-Square is 0.9792.

TABLE 1. Comparison of line widths between different schemes.

Scheme	Linewidth
compound cavity filtering	4MHz
saturable absorber	47kHz
cascaded add-drop fiber ring filter	1.1kHz

and the central wavelength of passband will change with temperature changes. By utilizing this feature, it is also possible to attempt to achieve wavelength tunable bidirectional single longitudinal mode fiber lasers.

IV. CONCLUSION

This paper proposes a combined filtering scheme using a bandpass filter and a cascaded add-drop type fiber ring filter, which can ensure bidirectional reciprocity in structure, including polarization state reciprocity. The influence of various parameters on the cascaded fiber ring filter is analyzed through simulation, and subsequent experimental parameters are determined. Experiments were carried out according to the parameters, and a bidirectional single longitudinal mode output was obtained. The bidirectional output linewidth was close to 1.1 kHz, lower than the previously reported tens of kHz level. The combined filtering scheme proposed in this paper uses standard optical devices and has a mature theoretical system, which is conducive to the subsequent application of bidirectional single longitudinal mode Er-doped fiber ring lasers.

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