Direct observation of beat-frequency switching in a self-sweeping fiber laser using variable space length

Kaile Wang
State Key Laboratory of Integrated Service Networks, School of Telecommunications Engineering, Xidian University
State Key Laboratory of Transient Optics and Photonics, Chinese Academy of Sciences
Xi'an, China
klwang1217@163.com

Zengrun Wen
School of Physics and Electronics, Shandong Normal University
Jinan, China
wenzengrun@163.com

Ping Wang
State Key Laboratory of Integrated Service Networks, School of Telecommunications Engineering Xidian University
Xi'an, China
pingwang@xidian.edu.cn

***Abstract*—Lately, a novel beat-frequency signal doubling phenomenon has been reported based on a self-sweeping fiber laser platform, which is essential for understanding the mechanism of the self-sweeping effect and the wavelength interval in sweeping operation. In this work, we studied the phenomenon using a variable space length. By controlling the cavity length (also known as "the spacing of longitudinal mode") and using a 1.8 m long fiber saturable absorber (FSA), we achieved the beat-frequency switching from the fundamental to the double frequency. Furthermore, a theoretical analysis was proposed to explain the phenomenon by calculating the reflected spectrum provided by the FSA and the change of the longitudinal mode in the cavity.**

Keywords—beat-frequency, single-frequency, self-sweeping, fiber laser

I. Introduction

Self-sweeping fiber lasers have attracted considerable attention due to their distinctive spectral and pulse dynamics. Currently, self-sweeping fiber lasers are classified into microsecond pulse type and continuous wave type based on their pulse characteristics [1,2,3]. In particular, the continuous wave type self-sweeping fiber laser can generate single-frequency output while achieving self-sweeping operation by forming a standing wave field in an unpumped fiber with a unidirectional ring cavity structure, which exhibits excellent coherence and has great potential for use in fiber sensing, LIDAR, and other fields [4,5].

Recently, single-frequency self-sweeping fiber lasers (SFSSFLs) have been extensively studied in Er and Yb fibers [2,5]. The continuous wave type self-sweeping laser has a dual-wavelength laser beat state, which is characterized by a stable amplitude modulation in pulse intensity and a beat signal in the radio frequency (RF) spectrum. This signal is consistent with the longitudinal mode interval in the cavity, indicating the wavelength switching interval. However, recent studies have revealed a new phenomenon, where the beat-frequency signal is twice as long as the longitudinal mode interval [6]. This implies not only a doubling of the self-sweeping interval, but also a doubling of the self-sweeping speed. Therefore, exploring the switching mechanism of this phenomenon is of great importance for the development of self-sweeping lasers.

In this work, we constructed a SFSSFL, where we introduced a piece of variable space lengths using a collimator and mirror. We observed the RF spectra under different space lengths, and the RF peak increased as the space length decreased. We developed a simulation of the FSA bandwidth to explain the switching of the beat-frequency.

II. Experimental Setup

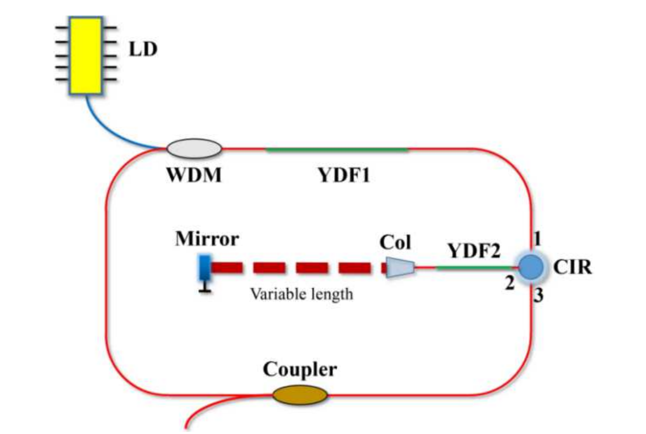

Fig. 1. Experimental setup of proposed fiber laser. LD: laser diode; YDF: Ytterbium-doped fiber; WDM: wavelength division multiplexer; CIR: optical fiber circulator; Col: optical collimator.

Figure 1 shows the experimental setup of SFSSFL. The pump source is provided by a 980 nm laser diode, which pumps the gain fiber (YDF1) using a 980/1060 nm wavelength division multiplexer. The cavity body contains WDM, YDF1, CIR, YDF2, Col, Mirror and Coupler. The CIRdetermines the clockwise direction of operated laser from port 1 to port 2 and port 2 to port 3. The high isolation between ports exists if it runs in reverse. Therefore, a standing-wave field is generated between the port2 of CIR and Mirror, where we place a piece of gain fiber (YDF2) to induce a dynamic grating with slight wavelength detuning that achieves the self-sweeping effect. Additionally, a collimator is used to guide the light from fiber into space, and the light beam will travel some distance in space and be reflected back into the collimator by the mirror. In this system, all components are fused well, and are matched with the operated wavelength. The details of devices are shown in our previous work [5].

III. Experimental result and discussion

A. RF spectral features

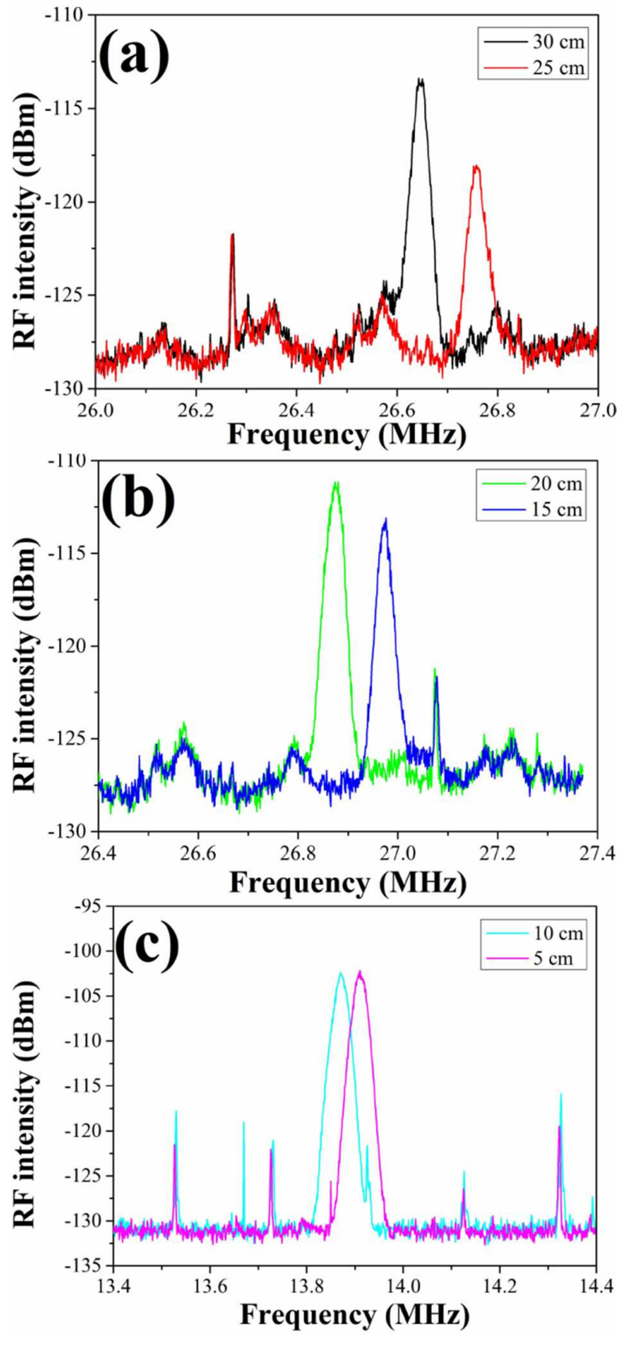

Fig. 2. RF spectra of fiber laser at different space lengths. Space length about 30 and 25 cm (a), Space length about 20 and 15 cm (b), and Space length about 10 and 5 cm (c).

Figures 2 show the results of RF spectra of SFSSFL at a pump power of 105 mW. In observation, the various lengths are changed six times, and these distances are 30, 25, 20, 15, 10, 5 cm, respectively. One can see that the data of 30 and 25 cm are depicted in Fig. 2(a), where the RF signals are 26.643 and 26.741 MHz, respectively. Fig. 2(b) exhibits the RF spectra when the space lengths are set as 20 and 15 cm, respectively, in which we can see the signals located at 26.874 and 26.976 MHz. The obvious difference occurs when the space length is adjusted as 10 cm, there is no signal beyond 20 MHz, and an RF peak generates at 13.869 MHz. With the space length decreasing to 5 cm, an RF peak also can be found at 13.913 MHz. Clearly, in this experiment, the RF peaks increase with the space length decreases, and the trend is same with our previous work. However, compared with Ref. [5], we used a longer FSA, and we fused a 1 m long single-mode fiber between Col and CIR. The ascending cavity length leads to the decrease of spacing of longitudinal mode.

B. Simulation result and discussion

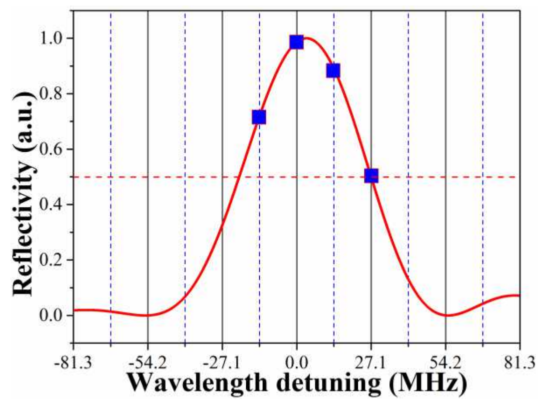

Fig. 3. Reflectivity of dynamic induced grating formed in FSA with a longitudinal mode interval of 27.1 MHz.

Let us talk about the switching phenomenon of beat-frequency. According to our experiment, the shortened cavity length forces the signals back from double frequency to fundamental frequency. The variation of cavity length is closely related to longitudinal mode spacing. But, the bandwidth provided by FSA does not change. Therefore, we simulate the reflected spectrum of dynamic induced grating formed in FSA. Here, the central wavelength is 1060 nm, and the length of FSA is 1.8 m. The simulated result is shown in Fig .3. One can see that a marked square is located at a point, where the horizontal is 27.1 MHz and the vertical axis is 0.5. If we make 27.1 MHz act as the spacing of longitudinal mode, we can see there are four longitudinal modes within the FWHM of FSA reflected spectrum. This value may be a conversion point, less than this value will appear twice the frequency spectrum, greater than this value will appear the fundamental frequency. Of course, the sweeping direction will change along with the switching of beat-frequency, which has been confirmed in Ref. [7].In fact, the switching of beat-frequency brings more changes, such as the sweeping rate, the sweeping direction for the self-sweeping characteristics. This will enable us to further control the self-sweeping output for future applications.

IV. Conclusion

In summary, we reported the switching phenomenon of beat-frequency in a SFSSFL. By decreasing the length between the Col and the mirror from 30 to 15 cm, the RF signals increased from 26.643 to 26.976 MHz, showing a regular variation. However, when the distance was set as 10 cm, the RF peak dramatically change into 13.869 MHz, and further occur at 13.913 MHz when the length became 5 cm. The phenomenon was explained by the simulation of reflectivity of dynamic induced grating, where the cavity length can control the switching of longitudinal mode. Our study uncovered the switching mechanism and will generate great impact on both basic research and application.

ACKNOWLEDGMENT

This work was supported by Natural Science Basic Research Program of Shaanxi (Program No.2023-JC-QN-0691), Open Fund of the State Key Laboratory of Transient Optics and Photonics, Chinese Academy of Sciences (SKLST202217).

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