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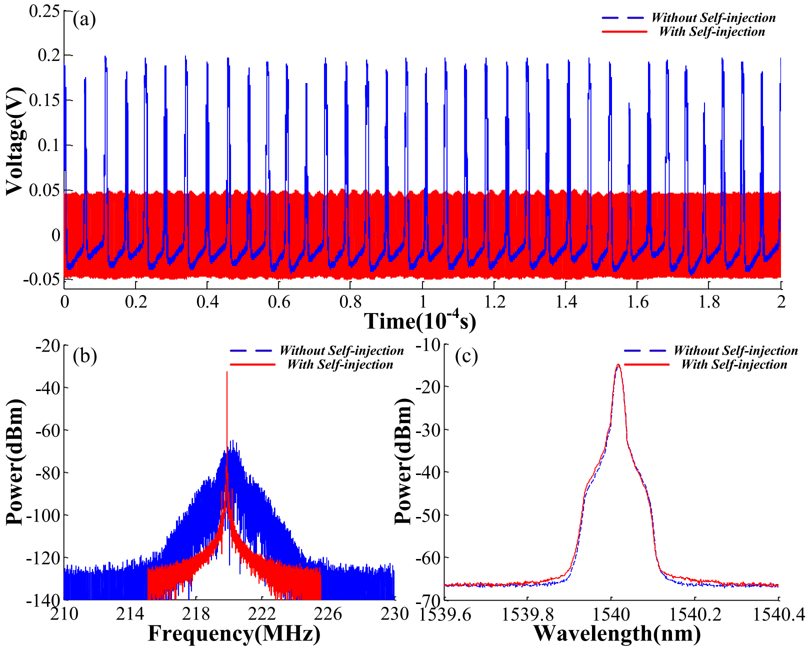

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Beat Frequency Characterization and Stabilization for Short-Cavity DBR Fiber Grating Laser Based Sensor

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Abstract: In this paper, we propose our observation, analysis, and alleviation method of the beat frequency fluctuation in short-cavity dual-polarization distributed Bragg reflector (DBR) fiber grating laser sensor in time and frequency domain. According to our observation, beat frequency fluctuation varies from 8 to 800 kHz under different pump power. Research shows frequency domain beat signal linewidth broadening aggravates beat frequency fluctuation due to time domain irregular self-pulsation effect. By introducing self-injection into laser cavity as an auxiliary pump laser with a circulator, self-pulsation effect in DBR fiber laser sensor can be greatly suppressed, resulting in the compression of frequency domain beat signal linewidth as well as the stabilization of beat frequency fluctuation. Experimental results demonstrate that beat frequency fluctuation can be greatly reduced from 800 to 8 kHz within 1 h through self-injection, which is significant for high-accurate sensing.

Index Terms: Fiber lasers, laser stability, optical fiber sensors, sensor phenomena and characterization.

1. Introduction

Fiber sensing technology has attracted massive attention due to its light weight, compact size, anti-erosion property, immunity to electromagnetic interference, and multiplexing capability. Among various kinds of fiber sensing components, the short-cavity distributed Bragg reflector (DBR) fiber laser has attracted considerable attentions for various sensing applications due to advantages of simple linear cavity configuration, single longitudinal mode operation with narrow line-width, low threshold and high efficiency [1], [2]. Various parameters of DBR fiber laser, for instance, laser power, wavelength and beat frequency, have been used in manifold optical sensors, such as the refractometer and thermometer implementing laser peak power and wavelength detection simultaneously [3], the refractometer utilizing the wavelength change of lateral-drilled DBR fiber laser [4], and the ultrasound detector using the variation of beat frequency [5].

Particularly, beat frequency, the frequency of beat signal generated from wavelength difference between orthogonal polarization states in short-cavity DBR fiber laser [6]–[8], is often used to interrogate measurands, such as strain [6], hydrostatic pressure [9] and twist [10], on account of the advantages of high signal to noise ratio (SNR) of laser, absolute coding of frequency domain signal and ultra-high frequency discrimination resolution of the electrical signal over other sensing parameters.

Sensing parameter stability is of crucial importance in high-accuracy sensing. Accompanied with sensitivity, sensing parameter stability determines the accuracy of sensor. Significantly, beat frequency stability of DBR fiber laser sensor is essential for achieving high-accuracy measurement. Few studies on beat frequency stability of DBR fiber lasers have been reported [11]–[13]. These researches mainly focused on the study of beat frequency fluctuation in frequency domain, and introduced several methods of beat frequency stabilization. For example, by using polarization-maintaining (PM) fiber and annealing, beat frequency fluctuation was decreased from 1.5 MHz to 0.1 MHz, due to the reduction of pump light polarization influence on fiber birefringence [11]. Through reducing the random backward reflection of laser cavity, beat frequency stability can be enhanced to ±5 kHz within 20-minute duration [12], [13]. However, neither the time domain beat signal variation nor the relationship between beat frequency fluctuation and pump power has been observed in these researches. The effectiveness and time duration of beat frequency stabilization is limited. Therefore, the method to realize high stability of the beat frequency should be systematically investigated.

In this paper, the dynamic change of short-cavity DBR fiber laser beat signal is comprehensively studied both in time and frequency domain. Experiments show that the shape of frequency domain beat signal line-width is related to beat frequency fluctuation, which can be altered with different pump and feedback conditions. The reason for pump power relevant beat frequency fluctuation aggravation is revealed, which is due to irregular self-pulsation variation in time domain. Furthermore, by simply introducing self-injection into laser cavity as an auxiliary pump, beat frequency stability can be enhanced from 800 kHz to 8 kHz, which will improve the measurement resolution of beat frequency based sensor greatly. Research in this paper is a supplementation to previous work, and the proposed method to improve beat frequency stability will be helpful for further research and applications in beat frequency based DBR fiber laser sensors.

2. Analysis of Beat Frequency Fluctuation

In our experiment, DBR fiber laser is composed of two 12 mm long high-reflectivity wavelength-matched fiber Bragg gratings (FBGs) centered around 1540 nm, with a 8 mm separation between FBGs, shown in Fig. 1(a). As depicted in Fig. 1(b), the total reflectivity of FBG-pair is around 43.8 dB, with reflectivities of 20.8 dB and 17.0 dB respectively for the two FBGs. The 3-dB line-width of transmission spectrum of the FBG-pair is 90 pm. Applying the theory in [7] to our system, the effective length of DBR fiber laser cavity is calculated to be around 12 mm, corresponding to a 68 pm (i.e. 8.6 GHz) separation of the longitudinal modes. The frequency spectrum of laser output is shown in Fig. 1(c), with only one beat signal around 200 MHz induced by the orthogonal polarization modes in DBR fiber laser, confirming the single-longitudinal mode operation of the DBR fiber laser. FBGs are inscribed on Fibercore M-12 erbium doped fiber (EDF) with the absorption coefficient of 11 dB/m at 980 nm and 16 dB/m at 1531 nm.

Due to stress and deformation in manufacturing, birefringence is generated in EDF, which will lead to small wavelength difference between two orthogonal polarization transverse modes in the single-longitudinal mode. Beat signal in DBR fiber laser is produced by the wavelength difference. The frequency of beat signal is often called beat frequency. By transferring ambient parameters into fiber laser cavity deformation, which will lead to birefringence change, a beat frequency variation is generated by the difference of the optical wavelength change between two orthogonal polarization modes in laser. Owing that the effects of temperature or axial strain variation on the refractive index changes of two orthogonal polarization modes are almost the same, the beat frequency of DBR fiber laser is insensitive to temperature and axial strain [10], [14]. While, pump polarization and lateral force will generate different influence on the refractive index of orthogonal polarization modes, beat frequency can vary from several MHz to several GHz. Frequency domain beat signal of the same DBR fiber laser under different lateral forces is shown in Fig. 1(d). Because of the

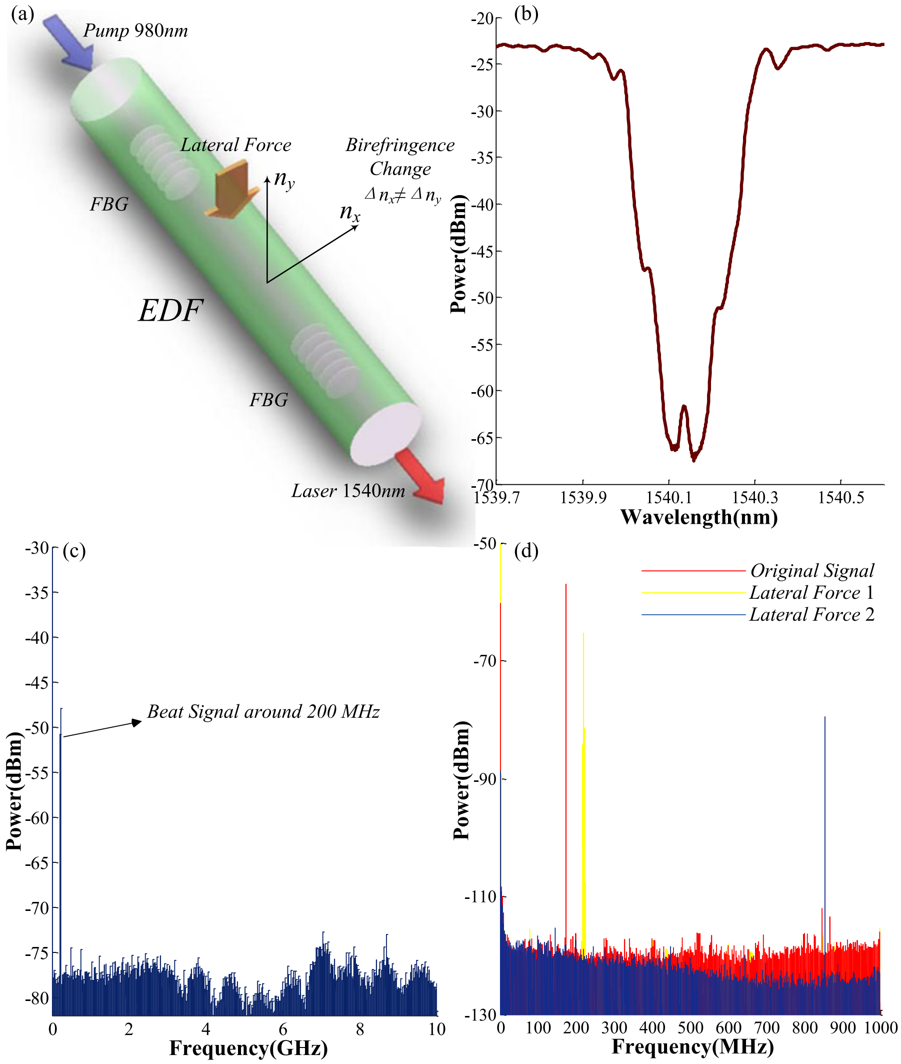

Fig. 1. (a) Schematic of the DBR fiber laser. (b) Transmission spectrum of FBG-pair. (c) Frequency spectrum of laser output. (d) Frequency domain beat signal shifts under different lateral forces.

heterodyne between orthogonal polarization modes, the high signal to noise ratio of laser and the high resolution of frequency demodulation, DBR fiber laser beat frequency sensors can achieve higher resolution than other sensors based on FBGs.

The ideal frequency domain beat signal should possess a single frequency component if there is no noise or disturbance, however, due to inhomogeneous birefringence along the fiber, atomic line-width, doppler broadening of gain medium and amplified spontaneous emission (ASE), frequency domain beat signal possesses a certain line-width which contains various frequency components, and the peak intensity of those frequency components fluctuates randomly. The center and peak value of frequency domain beat signal with a broad line-width is difficult to be fixed or precisely extracted, even with the identical DBR fiber laser, under same pump condition and by isolating possible external disturbances, which will reduce the resolution of sensor based on DBR fiber laser beat frequency severely. From what we have observed in the experiments, the stability condition of frequency domain beat signal line-width and beat frequency fluctuation might be even worse due to the dynamic status in fiber laser, which will be discussed in the following text.

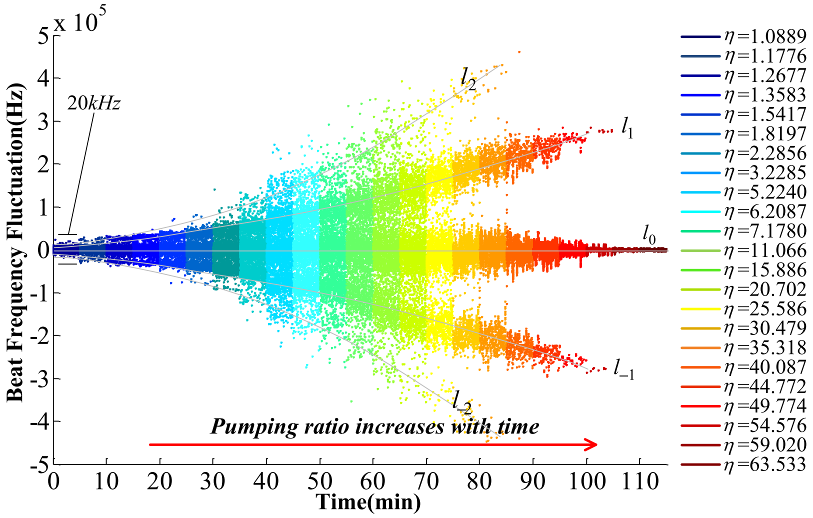

Fig. 2. Beat frequency fluctuation under different pump power.

To eliminate the influence of beat frequency fluctuation induced by DBR fiber laser cavity difference, the same DBR fiber laser is used throughout our experiments. Environmental temperature remains the same and external disturbances are isolated. First, we focus on the beat frequency fluctuation, an easy and intuitive way to show the stability of beat frequency. By tracking the peak intensity value of frequency domain beat signal spectrum, beat frequency fluctuation with time can be extracted. The beat frequency fluctuation under different pump power conditions, each of which with a five-minute duration, is depicted in Fig. 2.

We define the pump power versus threshold power of DBR fiber laser as pumping ratio $\eta = P/P_{th}$, where P is the pump power, P_{th} is the threshold pump power. The threshold pump power of DBR fiber laser in experiment is around 7.74 dBm. By increasing the pump power gradually from near the laser threshold to $\eta = 63.533$, beat frequency fluctuation increases from 20 kHz to 800 kHz first, but decreases suddenly after $\eta = 40.087$. The evolution of beat frequency fluctuation with increasing pumping ratio is not uniform, but has dynamic changes. Five major frequency splitting lines $l_{-2}l_{-1}l_0l_1l_2$ can be seen in beat frequency fluctuation diagram as shown in Fig. 2. The outmost two frequency splitting lines $l_{-2}l_2$ disappear after $\eta = 40.087$, but the inner two frequency splitting lines $l_{-1}l_1$ still exist until $\eta = 54.576$. Afterwards, only the beat frequency splitting line l_0 remains, while the beat frequency fluctuation is reduced and no more change or splitting is observed.

To have a deep understanding of the beat frequency fluctuation tendency in Fig. 2, we now take a look at variations of beat signal of the same DBR fiber laser under different pump power in time and frequency domain, as shown in Fig. 3.

As the typical beat signals depicted in Fig. 3(a)–(f) for time domain, and Fig. 3(g)–(l) for corresponding frequency domain, respectively, it can be seen that the time domain beat signal possesses various shapes from the unstable pulsation to stable pulsation. In Fig. 3(a) and (g) for $\eta = 1.0889$, time domain beat signal is in a continuous wave (CW) shape, and the frequency domain beat signal possesses narrow line-width, the beat frequency fluctuation is around 20 kHz. However, the SNR of frequency domain beat signal is extremely low which is disadvantageous for data acquisition and measurement. In Fig. 3(b) and (h) for $\eta = 15.886$, irregular pulsation emerges in time domain, different pulsation periods possess distinctive pulse shapes and frequency spectra. The total frequency spectrum of irregular pulsation will be composed of various frequency components generated by individual pulsation periods, leading to a broad line-width with varied peak frequency at different times, which aggravates the beat frequency fluctuation to around 600 kHz. Further, as shown in Fig. 3(i) and (j), by increasing pumping ratio to $\eta = 40.087$ and $\eta = 63.533$, time domain beat signal pulsation becomes more and more regular, from period-doubling pulsation in Fig. 3(c), repeating

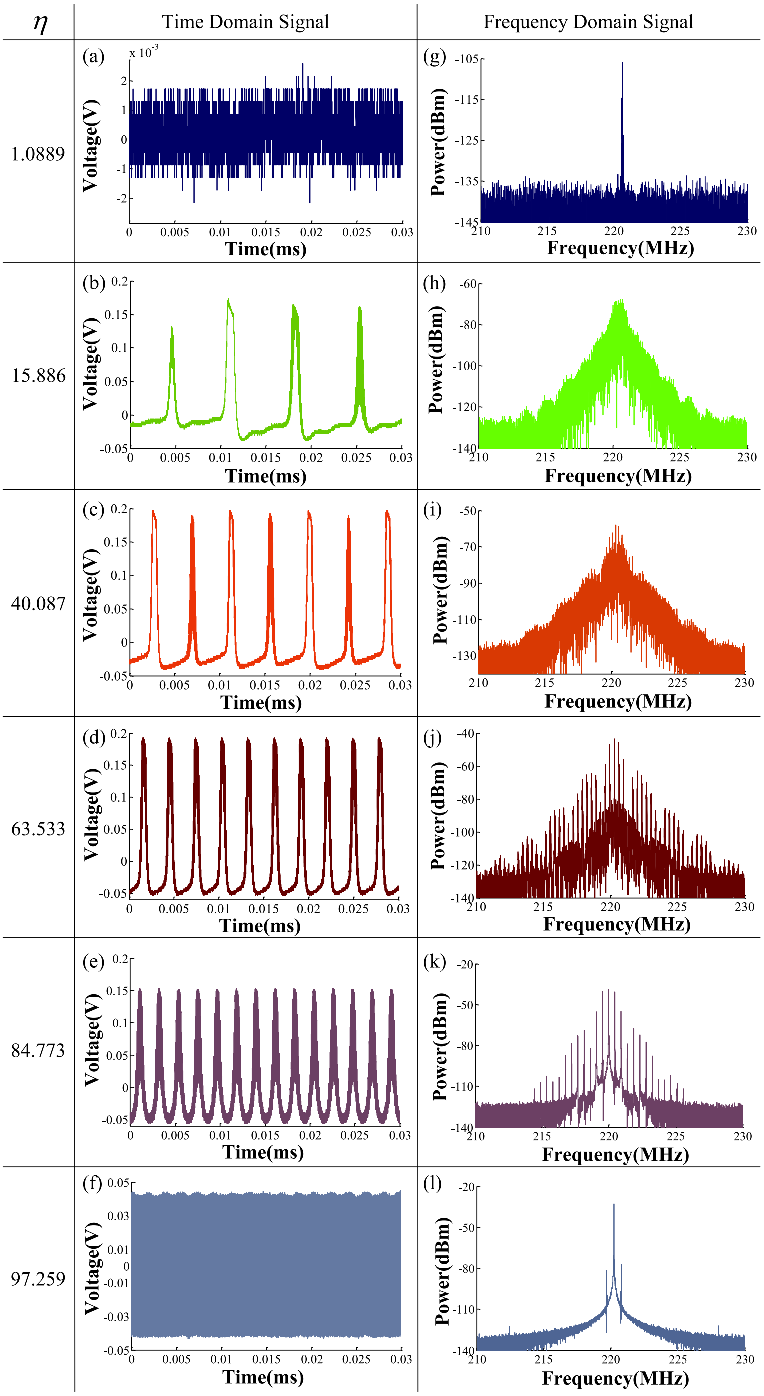

Fig. 3. (a)–(f) Beat signals of DBR fiber laser in time domain under different pumping ratio. (g)–(l) Beat signals in frequency domain corresponding to (a)–(f), respectively.

every two pulses, to stable pulsation in Fig. 3(d), and a higher pulse repetition rate is observed. Frequency domain beat signal becomes broader, and a few discrete frequency peak lines appear in the spectrum. These discrete frequency peak lines can be considered as the result of amplitude modulation induced by self-pulsation. The frequency intervals between these discrete frequency peak lines are corresponding to the pulse repetition rate in time domain, and the variation of frequency peak power among the strongest five frequency peak lines in Fig. 3(i) and (j) induces the five major frequency splitting lines in Fig. 2. Beat frequency fluctuation reduces from around 800 kHz to 500 kHz and then to less than 20 kHz, as depicted in Fig. 2. The beat frequency fluctuation reduction is induced by an alleviated competition among the intensity of frequency peak lines around the center of frequency domain beat signal spectrum. When $\eta = 63.533$, beat frequency fluctuation is greatly reduced, however, the frequency domain beat signal line-width is still broad with numerous frequency peak lines, which may aggravate beat frequency fluctuation under external disturbance, and time domain pulsation is severe which is detrimental for optical components and photo detector (PD) in long-term operation.

By further increasing the pumping ratio, we can attain the time domain beat signals in Fig. 3(e) and (f), and the corresponding frequency domain beat signals in Fig. 3(k) and (l). When $\eta = 84.773$, time domain beat signal pulsation becomes even more regular than that when $\eta = 63.533$. The repetition rate increases, while the amplitude of pulsation decreases. The noise of frequency domain beat signal in Fig. 3(k) reduces, with several clear discrete frequency peak lines remained. Under extremely high pumping ratio when $\eta = 97.259$, time domain beat signal pulsation is eliminated and the frequency domain beat signal possesses only one single frequency peak, as illustrated in Fig. 3(f) and (l).

As mentioned above, time domain pulsation in DBR fiber laser will lead to the broadening of beat signal line-width in frequency domain, which will aggravates beat frequency fluctuation. The observed pulsation named as self-pulsation is caused by the interaction and energy transfer between erbium ion-pairs in EDF [15]. And the evolution of pulsation shapes from the chaotic behavior in Fig. 3(b) to period-doubling pulsation in Fig. 3(c) and then to stable pulsation in Fig. 3(d), can be perceived as bi-stability [16], [17] caused by frequency locking between the two orthogonal polarization modes in DBR fiber laser.

With higher pumping ratio, the self-pulsation will disappear due to the gain uniformity increase caused by the absence of weakly pumped region in fiber under high pumping ratio [18], as the condition in Fig. 3(f), the corresponding frequency spectrum will possess only one single narrow line-width frequency peak, as displayed in Fig. 3(l). Without competition between different frequency peaks, the beat frequency stability will be enhanced. However, the pumping ratio for self-pulsation suppression is extremely high, which will inhibit the application of DBR fiber laser sensor. Thus, we expect to eliminate the self-pulsation of DBR fiber laser under lower pumping ratio and increase the long-term beat frequency stability.

By introducing auxiliary pump with operating wavelength near lasing wavelength, which helps maintain the population of the erbium ions in the excited state and mitigates the rapid drain of erbium ions from the excited state back to the ground state induced by erbium ion-pairs, the self-pulsation effect in erbium doped ring fiber laser can be eliminated [19]. Here, we propose to use the self-injection as an auxiliary pump to eliminate the self-pulsation in DBR fiber laser, which could greatly reduce the complexity of system, make the best use of laser from both ends of DBR fiber laser output and enhance the effectiveness of self-pulsation suppression due to the wavelength matching between laser in cavity and laser injected.

3. Self-Pulsation Elimination and Experimental Results

The schematic diagram of the stable DBR fiber laser system with self-injection is shown in Fig. 4. The laser is pumped by a 980 nm pump source whose output power is tunable and can reach 600 mW through a 980/1550 nm wavelength division multiplexer (WDM). By using higher feedback power as auxiliary pump, the suppression region of fiber laser self-pulsation will be broader under different pumping ratio [19]. And the realization of beat frequency stabilization will become more easily. Here, a circulator is exploited to inject all the output of DBR fiber laser back into the laser cavity, while being used as an isolator and an output coupler. The polarization state of the injected laser is controlled by a polarization controller (PC), and an isolator is used to eliminate the unwanted reflection light to the laser cavity. One PD is utilized to transform the optical signal into electrical signal which can be acquired and processed through NI data acquisition system. In the experiment,

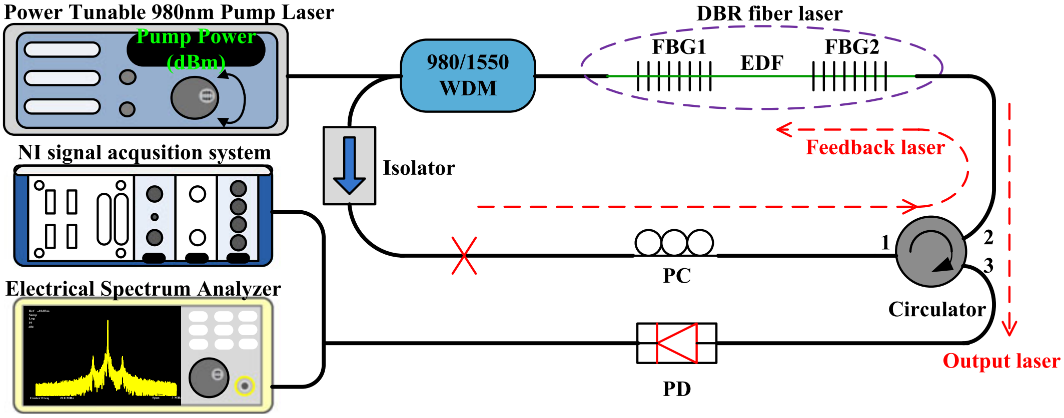

Fig. 4. Experimental setup of the DBR fiber laser system with controllable pump power and self-injection.

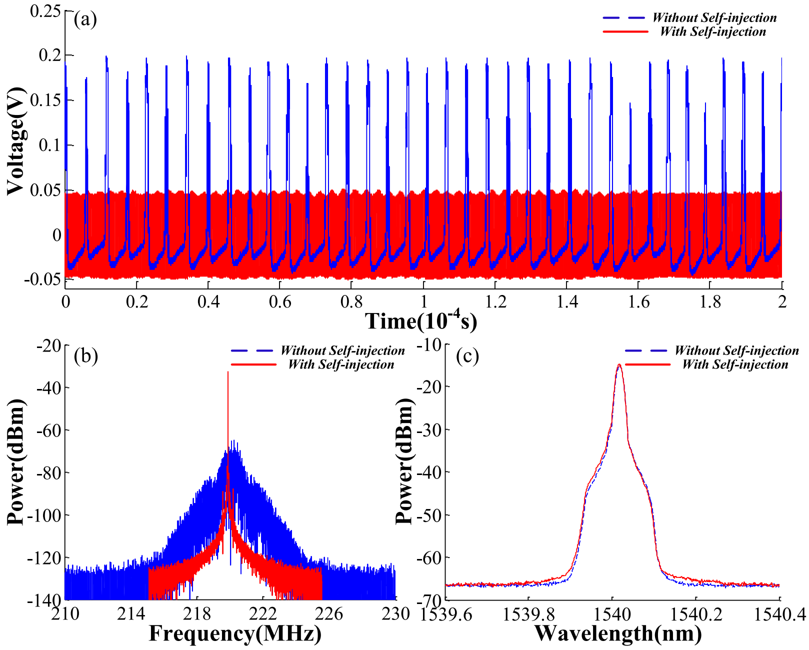

Fig. 5. (a) Time domain beat signal without and with self-injection. (b) Frequency domain beat signal without and with self-injection. (c) Optical spectrum of DBR fiber laser without and with self-injection.

except for the DBR fiber laser cavity, all the other fibers and optical components are PM to reduce the beat frequency fluctuation induced by random polarization variation [11]. By connecting or disconnecting the fiber at the cross marked point in Fig. 4, the experimental results with and without self-injection can be observed, respectively.

With the self-injection method, the melioration of beat frequency fluctuation is inspected. Through connecting the fiber at the cross shown in Fig. 4, laser feedback is injected into the cavity, with the pumping ratio $\eta = 25.586$. Fig. 5(a) shows time domain beat signals without self-injection and with self-injection. It is obvious that the self-pulsation is completely wiped out with self-injection. While in Fig. 5(b), compared with the broad and multi-peak line-width frequency domain beat signal without self-injection, the line-width of frequency domain beat signal with self-injection can be compressed to only one main single peak with two very low and symmetrical side peaks, as illustrated by red curve in Fig. 5(b). Moreover, the SNR of the frequency domain beat signal is remarkably enhanced to be more than 80 dB. The optical spectrum without injection and with injection is shown

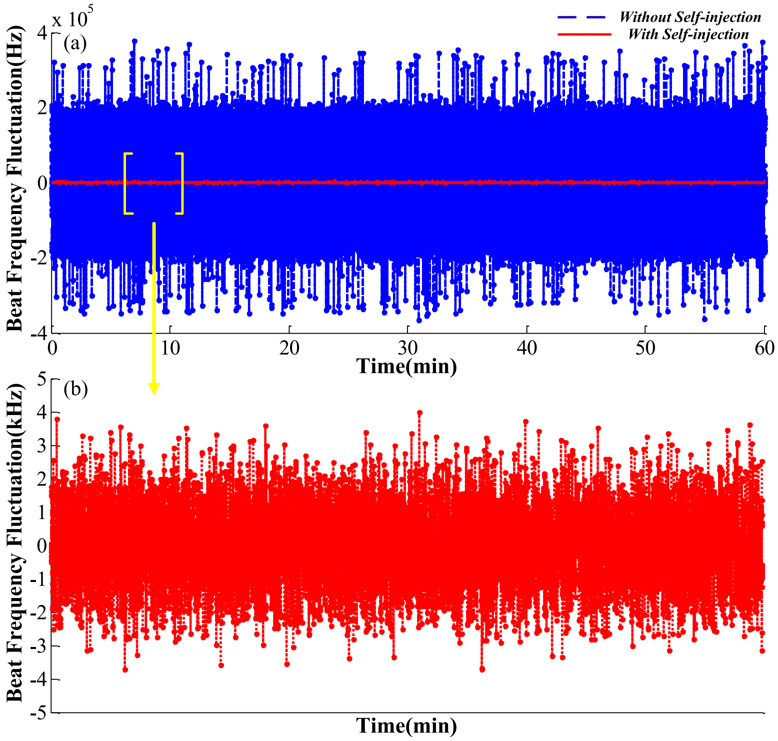

Fig. 6. (a) Beat frequency fluctuation without and with self-injection. (b) Enlarged picture of beat frequency fluctuation with self-injection.

in Fig. 5(c) which remains almost the same after injection, with only a slight increase in optical power. As a result, the self-pulsation can be eliminated with self-injection, suppressing frequency domain beat signal line-width, without interfering with the optical property of DBR fiber laser output.

In order to investigate the stability of beat frequency, the traces of beat frequency fluctuation within 60 minutes without and with self-injection under the same pumping ratio $\eta = 25.586$ are recorded and compared in Fig. 6(a), and an enlarged figure is depicted in Fig. 6(b). A distinct improvement of the beat frequency fluctuation from nearly 800 kHz to less than 8 kHz is achieved with self-injection, which could greatly increase the measurement precision about two orders of magnitude for DBR fiber laser sensors. And the pumping ratio to reach CW output of time domain beat signal can be significantly reduced from $\eta = 97.259$ to $\eta = 25.586$, which is meaningful for practical operation.

4. Conclusion

We analyzed the characteristics of DBR fiber laser beat signal both in time and frequency domain under different pump conditions, and found out that the aggravation of the beat frequency fluctuation is caused by irregular self-pulsation in DBR fiber laser. Furthermore, we proposed self-injection to enhance the stability of beat frequency. By implementing an auxiliary pump with self-injection, the gain uniformity of the EDF can be increased, which eliminates the self-pulsation region of the DBR fiber laser. With self-injection, a significant improvement of beat frequency stability with the fluctuation from around 800 kHz to less than 8 kHz can be achieved under relatively low pump power, which is of profound significance to the ultra-high precision sensors based on DBR fiber laser.

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