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A Self-Mixing Microvibration Measurement System of a π-Phase Shifted DFB Fiber Laser

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Abstract

Recently, with the rapid development of precision machining, microvibration measurement is required for the manufacturing and installation of parts and components. In this paper, a self-mixing microvibration measurement system of a π-phase shifted Distributed feedback (DFB) fiber laser is introduced. An all-fiberized configuration Er^{3+}-Yb^{3+} co-doped DFB fiber laser was used as light source, in which an active π-phase shifted fiber Bragg grating (FBG) was wrote on Er^{3+}-Yb^{3+} co-doped fiber. Using this, it can easily get a single-mode lasing with narrow linewidth. Experimental results demonstrate that the amplitude of vibration can be achieved down to $\lambda/5$ without any modulation parts while utilizing the reflecting mirror. It is in good agreement with the theoretical analysis and very helpful in proving sensitivity and stability of the measurement system. In addition, remote vibration measurement with a distance of 20 km is also realized with this system.

Keywords

Self-Mixing, Distributed Feedback Fiber Laser, Microvibration Measurement, Remote Vibration Measurement

1. Introduction

In 1963, King and his partners first reported the phenomenon called "self-mixing interference (SMI)" [1]. They found that the intensity modulation caused by a movable external mirror was similar to that produced by a conventional optical interferometer. SMI can be realized by the reflected portion of light mixing actively with the light inside the cavity, then causing a modulation of the output power of the laser.

During the last decades, many researches were focused on this phenomenon, which can be used to measure the vibration [2], velocity [3], displacements [4] and many physical parameters [5] [6]. Because SMI would produce the intensity variations which can be detected easily by a photodetector (PD), and from this the information of the environment changes could be gotten. Furthermore, SMI has a compact setup, and is easy to deploy in the field, since it only needs to align the laser to the target, no other additional optical elements are required.

Recently, much attention has been paid on the self-mixing effect of fiber laser for low noise, compactness, resisting the electromagnetic interference, high slope efficiency. But conventional fiber lasers have excessive cavity length that may induce hops to adjacent cavity modes, increase the photon cavity lifetime and reduce the sensitivity to optical feedback. To overcome these weaknesses, the cavity should be sufficiently short such that the mode spacing is comparable to the grating bandwidth. In 2011, our group used Er^{3+}-Yb^{3+} codoped Distributed Bragg reflector (EYDBR) fiber laser which can keep high sensitivity for vibration measurement [7]. In 2012, the maximum range of the remote sensor by the EYDBR fiber laser that is up to 20 km was discussed [8].

Distributed feedback (DFB) fiber lasers became attractive in the communication and sensing areas, for the very short length of cavity that can provide stable single longitudinal mode and single polarization operation and the emitted wavelength can be set accurately with passive stabilization. They are compatible with fiber inherently, so they can be used as light source of optical fiber sensing for ultra-distance, ultra-high precision, hypersensitized sensing. Additionally, they have low phase noise and low relative intensity noise.

In this paper, an Er^{3+}-Yb^{3+} co-doped active phase-shift fiber grating with an optimum grating length of 50 mm was used. Under a pump at 980 nm, the output lasing at 1550 nm was generated. In part 2, a self-mixing model in a π-phase shifted DFB fiber laser was introduced. And the theoretical mode was built and simulated. In part 3, this system was used to measure the microvibration. In part 4, the results of the theoretical mode were compared with the experimental results. The conclusion was given in part 5.

2. Methodology

2.1. Theoretical Analysis

In this section, a theoretical mode of DFB fiber laser were built on the effective cavity model, and then the three mirror cavity model of the self-mixing effect which has been extensively analyzed in the literatures [9] [10] [11] was use to approach and schematize.

DFB fiber laser provided lasing from the result of the signal generation by the gain medium and the feedback by the grating.

A single phase shift DFB fiber laser cavity and the three mirror cavity model are shown in **Figure 1**. The phase shift at $z = z_\theta$, this position determines the uni-directionality of the laser output [12]. P_{pin} and p_{lout} are the forward and

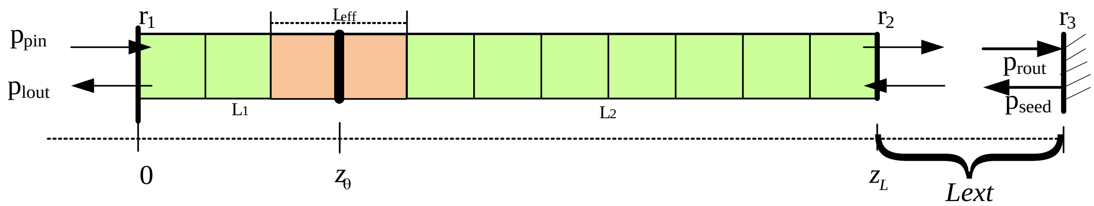

Figure 1. Schematic of a DFB fiber laser with external optical feedback: z_0, the position of the π-phase shifted in fiber grating; L_{eff}, the length of the effective cavity; L_1 - L_2, the lengh of the left and the right side of the position of the π-phase shifted in DFB fiber laser cavity; r_1 - r_3, reflectivity of the grating ends and the external reflector.

backward light power at $z = 0$, and p_{rout} and p_{seed} are the forward and backward light power at the fiber end facet $z = z_L$ which reflected by the external reflector. In our simulation, pumped from left end, output is from right end, and the length of the Er-Yb co-doped fiber DFB laser is 50 mm, optimum coupling coefficient around 150 mm^{-1} and the phase-shift located at $z = 29$ mm, L_{efft} is 6.5 mm. Also, output power depends on the grating strength $\kappa(z)$. Here grating is not apodized therefore coupling coefficient $\kappa(z)$ is constant. Intensity builds around the place of phase shift in such a cavity, went into the gratings, intensity drops dramatically. So effectively signal is confined around phase-shift by two strong reflectors of length L_1 and L_2, thus the reflection coefficients of the grating approximated as [13]:

$$r_i \approx -\tanh(\kappa_i L_i), i = 1, 2, \cdots \tag{1}$$

For most practical applications, the gain is small compared to the coupling coefficient, Optimum position of phase-shift and optimum grating strength define the optimum reflectivities of these two grating segments on both sides of the phase shift.

The penetration depth D which is known as the effective distance that fields propagate into a grating, then the total length of the effective cavity could be calculated by added them up [13].

$$L_{eff} = D_1 + D_2 \approx -\left(\frac{r_1}{2\kappa_1} + \frac{r_2}{2\kappa_2}\right) \tag{2}$$

Here D_1 and D_2 are the penetration depths on the left and right of the phase shift into the grating.

In the F-P cavity, the signal light and the pump light transmitted in the fibers along the forward and backward, and reflected by the each end of the part of grating, thus analyzed the influence of pump power, internal loss and length of fiber grating in Er^{3+}-Yb^{3+} co-doped DFB fiber lasers [14]. To analysis the effect of self-mixing, a seed light represented the feedback light from the external mirror [15] was set as shown in **Figure 1**.

Assuming that the external reflector was drove by a sinusoidal signal, so the length of external cavity changed periodically. The variable quantity of the external cavity can be expressed as follows:

$$\Delta L_{ext}\left(t\right)=A\cos\left(\omega_0 t+\varphi_0\right) \tag{3}$$

ω_0, φ_0 were the circular frequency and the initial phase of the driving signal.

In weak feedback regime, the effective reflection of the right end of the DFB FL could be expressed as:

$$r=r_2+\left(1-r_2\right)^2 r_1\exp\left(-i\omega\tau\right) \tag{4}$$

ω is the frequency of the laser, c is the light velocity in vacuum, $\tau = 2L_{ext}/c$ is the external round-trip time. r_1, r_2 are the reflectivity of the end of the grating and the surface of the feedback.

Thus, the seed light can be described as follows:

$$P_{seed}=\left(1-\kappa\right)r^2 P_s^{out} \tag{5}$$

κ is the coupling coefficient, P_s^{out} is the output power of the DFB fiber laser.

As our previous study [15], the laser output power is given by

$$p_{laser}=\varepsilon\left(1-r_1\right)P_r^{out}\exp\left(-\alpha_s L+p_s^{abs}/p_{ss}+p_p^{abs}/p_{ss}\right) \tag{6}$$

ε is the total attenuation factor, α_s is the small signal absorption coefficient, p_s^{abs}, p_p^{abs} are powers of the absorbed in one round trip, p_{ss} is the power of the saturated absorption.

The output power of SMI signal can be obtained based on the above study was shown in **Figure 2**.

2.2. The Vibration Measurement System Based on DFB FL

A self-mixing system using DFB fiber laser is showed in **Figure 3**. The pump light of 980 nm was coupled into the Er^{3+}-Yb^{3+} codoped DFB fiber laser through a wavelength-division multiplexer (WDM 1) in the common port of the WDM.

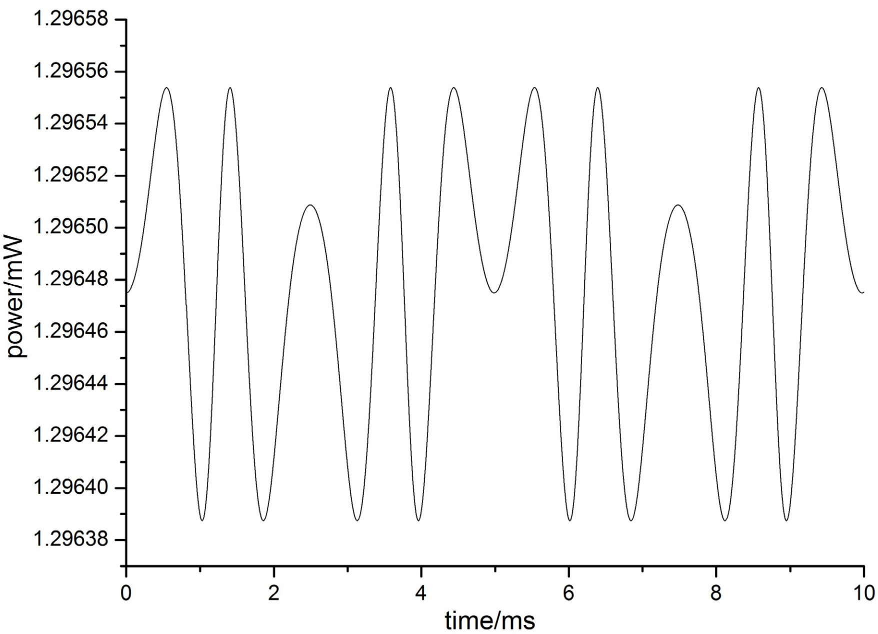

Figure 2. Simulated self-mixing signal with 1000 nm, 200 Hz.

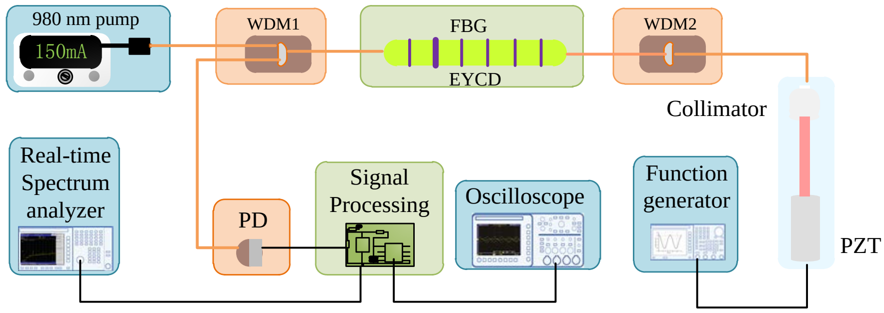

Figure 3. Schematic diagram of experimental set-up.

A single longitudinal (SL) mode lasing (1550 nm) emitted from the DFB FL, coupled into another WDM 2. The signal arm focused onto a loud speaker through a collimated lens. The initial distance from the lens to target was 5.0 cm. On the surface of the speaker stuck a mirror, and a function generator (Tektronix AFG3102) was used to driver it. The monitoring arm was detected by a photo diode (PD) followed by a signal processing circuit, which includes transimpedance amplifier, filters and fur amplifier.

In the specific experiment of microvibration measurement based on the all fiber distributed feedback fiber laser self-mixing micro interference vibration sensor system, the feedback object is piezoelectric ceramic, the vibration range is from nanometer to centimeter, and its vibration amplitude is proportional to the driving voltage. Therefore, by changing the voltage of the driving signal provided by the signal generator, simple harmonic microvibration of nanometer can be achieved. However, due to the limitation of the range of the output signal of the signal generator (the minimum is 20 mV), the minimum amplitude of PZT that can be achieved in the experiment is 69 nm.

3. Experimental Results

3.1. Characteristics of DFB FL

The spectral linewidth of laser was measured by a spectrograph (Yokogawa AQ6370C Optical Spectrum Analyzer) shown in Figure 4. In Figure 4, the 3 dB bandwidth of the laser is about 0.01 nm. But the real spectral bandwidth is much narrower than which is shown in Figure 4, because of the resolution ratio of the spectrograph is 0.02 nm, the measurement below it is not reliable.

Then the delayed self-homodyne measurement technique was used to investigate the spectral linewidth. The laser beam is split into two beams, one of them delayed by 20 km single mode fiber, that can generated the beat signal by interferometer. The result is shown in Figure 5. In Figure 5, the result was measured by a spectrum analyzer (Tektronix RSA-3408B Real-Time Spectrum Analyzer) using Exponential curve fitting method (for the output power in dBm as a unit) could get that the 3dB linewidth of the optimized system is about 0.5 kHz which is much narrow than the conditional DBR FL. Because longitudinal mode spacing is inversely proportional to the laser cavity length, that by decreasing cavity

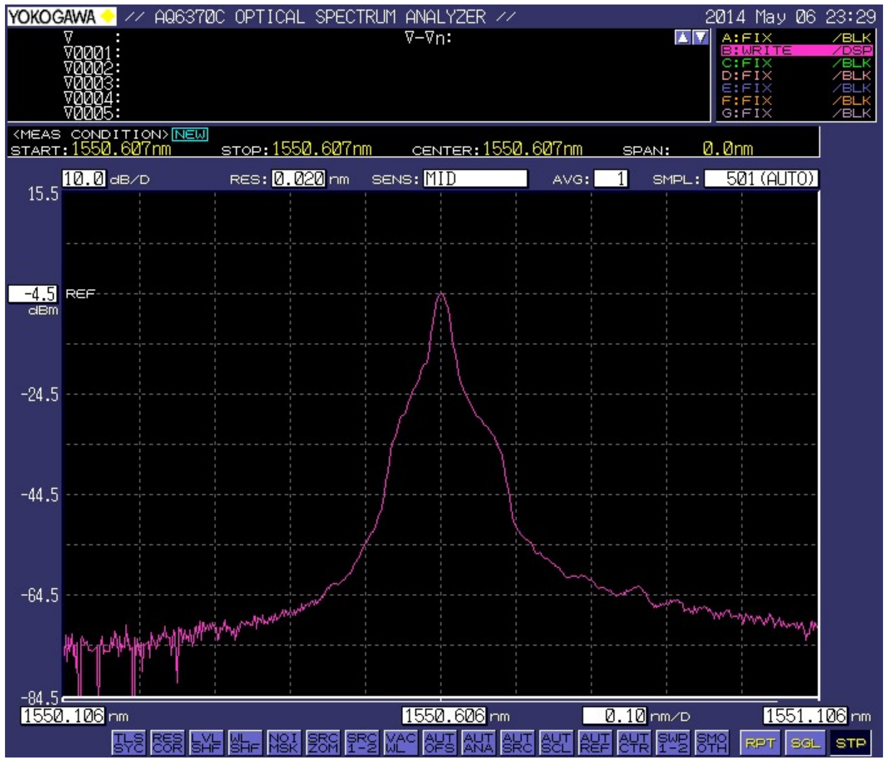

Figure 4. Frequency spectrum of DFB FL.

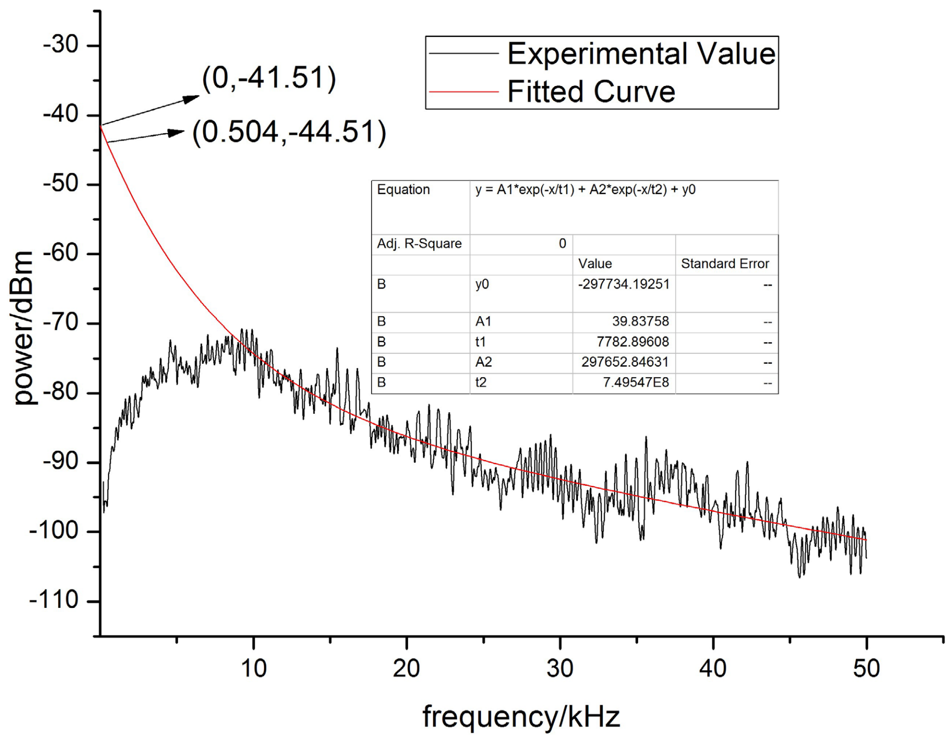

Figure 5. The spectral linewidth of the DFB FL.

length of longitudinal mode spacing is greater than the bandwidth of the frequency selective device, make only a longitudinal mode bandwidth conditions, stable single longitudinal mode output can be obtained, inhibit mode jump.

3.2. Experimental Result

A highly sensitive all fiber distributed feedback fiber laser is used in the micro-vibration measurement system to improve the system sensitivity. The driving signal of piezoelectric ceramics in the experiment is shown in **Figure 6(a)** and **Figure 6(b)**. The lower channel has three color sinusoidal curves: red dotted

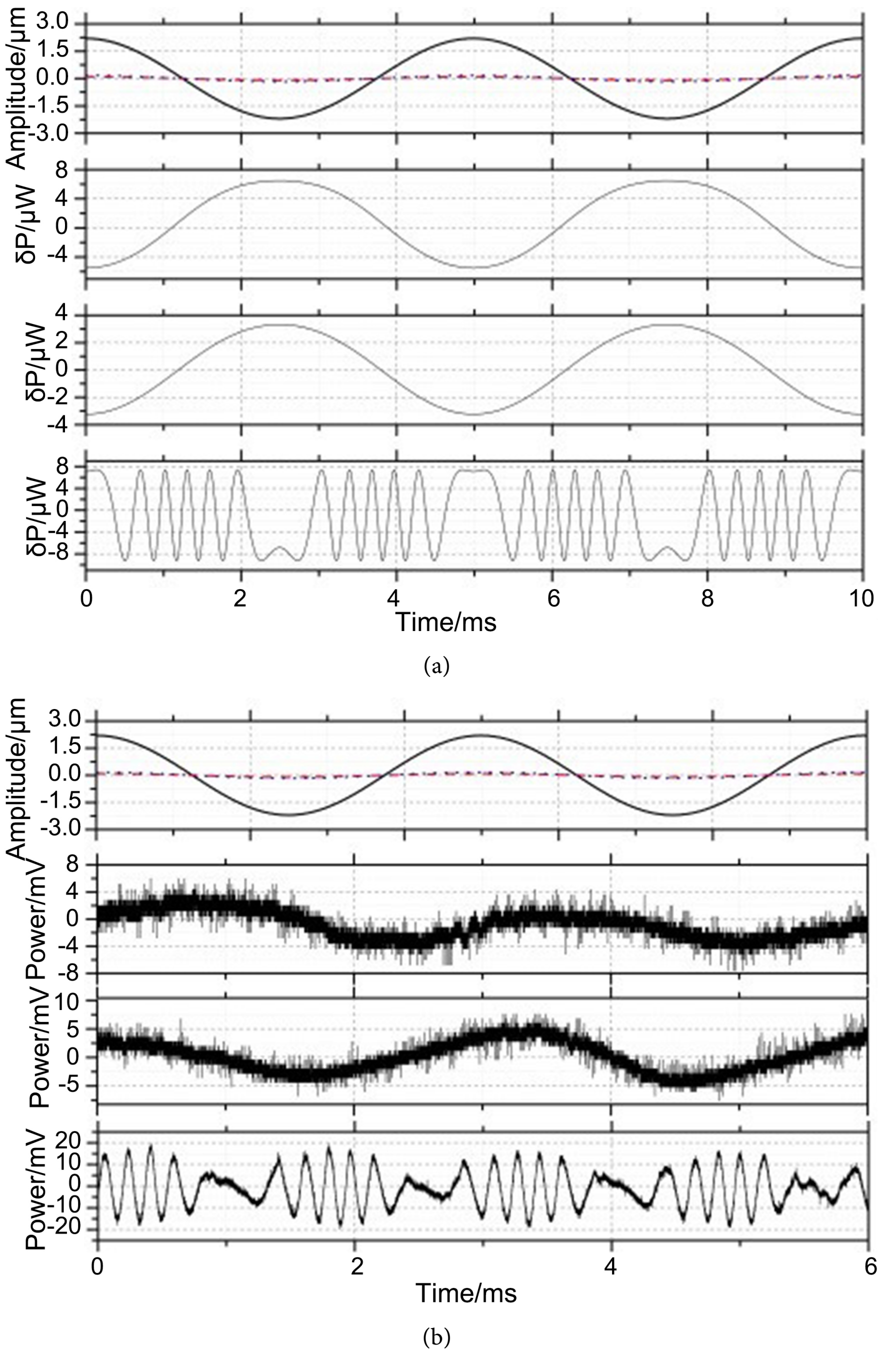

Figure 6. Self-mixing interference signals. (a) Analog signal diagram; (b) Signal diagram measured in experiment.

line, blue dotted line and black solid line. The red dotted line, blue dotted line and black solid line correspond to different amplitudes respectively: 97 nm, 169 nm and 2200 nm. In **Figure 6(a)**, the three curves of the upper channel correspond to the waveform of self-mixing signal generated under the driving limit of each amplitude simulated at 380 Hz. The black solid line corresponds to a typical self-mixing interference signal waveform whose amplitude exceeds a complete wavelength. Accordingly, the red dotted line and blue dotted line are the waveform of sinusoidal self-interference signal when the amplitude is lower than 200 nm. The three curves of the upper channel in **Figure 6(b)** correspond to the experimental results corresponding to the simulation results displayed in the oscilloscope.

When the vibration amplitude of piezoelectric ceramics is lower than 200 nm, the waveform of self-mixing interference signal appears like a sinusoidal curve, and the peak value of the waveform is proportional to the actual amplitude of piezoelectric ceramics. Piezoelectric ceramics are directly driven by a function generator, which can provide a minimum vibration signal amplitude of 20 mW. The amplitude of piezoelectric ceramics is changed by changing the driving voltage, and the vibration amplitude is kept below the range of 200 nm, so as to realize the measurement of microvibration with different amplitudes.

The comparison diagram of experiment and simulation results is shown in **Figure 7**. The black curve corresponding to the left vertical axis represents the actual amplitude of PZT in the range below 200 nm. The blue dot corresponding to the right vertical axis represents the experimental measurement value calculated from the peak to peak value of the mixed signal power displayed by the oscilloscope at the same amplitude as the black dot. The experimental results of the measurements shown in **Figure 7** are consistent with the trend of the simulation

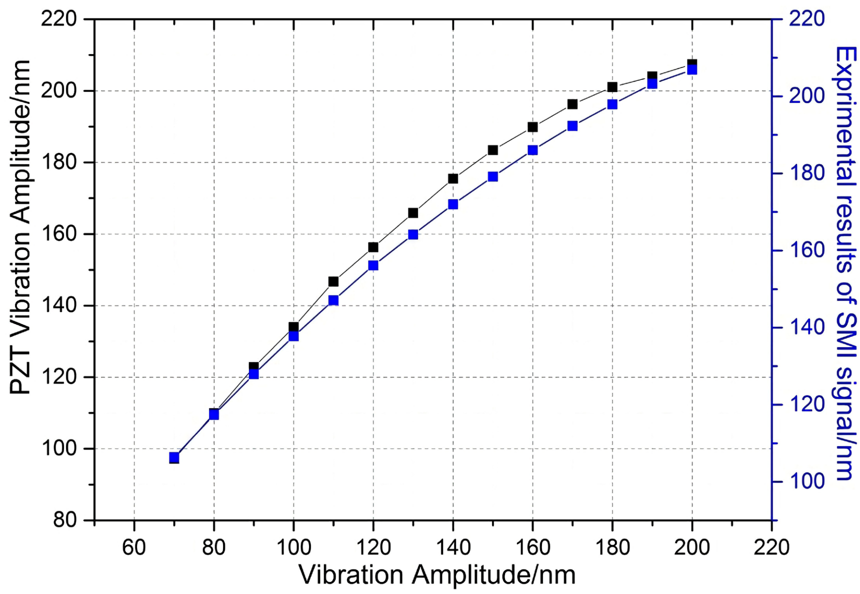

Figure 7. Comparison between experimental results of self-mixing microvibration measurement and actual amplitude of PZT.

results. Obviously, using our system, the amplitude range of measurement can be significantly expanded than that of similar systems reported previously (previously close to 400 nm, now expanded to 70 nm).

In order to better compare the actual amplitude of the experiment and PZT in **Figure 7**, an error chart was made for comparing the experimental data of self-mixing microvibration measurement with the actual amplitude of PZT, as shown in **Figure 8**. The maximum measurement error is 9.17 nm.

The error can be attributed to the following influencing factors: the self-mixing interference signal graph displayed in the oscilloscope is the electrical signal graph through the photodetector and signal processing circuit, which may cause signal distortion due to amplification and filtering, leading to errors; Different heat dissipation state and uneven temperature distribution will affect the shift of grating center wavelength in all fiber distributed feedback fiber laser, resulting in calculation error.

The traditional research of self-mixing interference vibration measurement technology is mainly carried out under the condition of space light feedback, and the feedback light is easy to be affected by the surrounding environment; At the same time, due to the phenomenon that a large amount of energy is dissipated and absorbed in the space propagation of light, and it is difficult to arrange an effective transmission optical path in the actual environment, it is difficult to achieve remote measurement. However, all optical fiber transmission can avoid the above problems. Therefore, a 20 km long single-mode optical fiber was introduced into the third port of the wavelength division multiplexer and the collimating lens to achieve remote microvibration measurement.

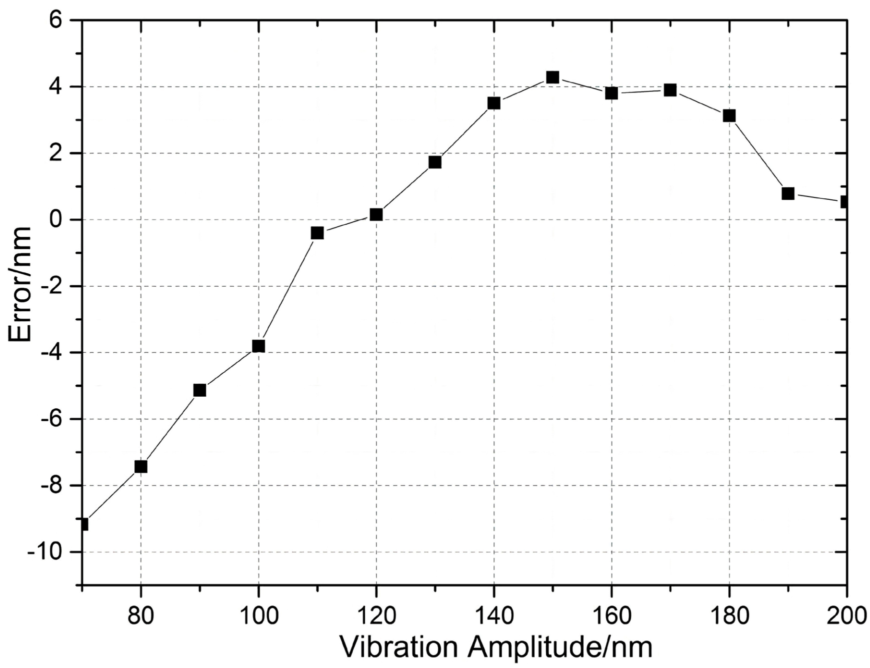

Figure 8. Error chart of comparison between self-mixing microvibration measurement Data and PZT actual amplitude.

A radio-frequency (RF) spectrum analyzer (Tektronix RSA-3408B real-time spectrum analyzer) was used to get the spectrums of the self-mixing signal which showed in **Figure 9**.

When the external single-mode fiber is 20 km long, the output power of all fiber distributed feedback fiber laser decreases to one fifth of the initial value, so it is difficult to observe obvious self-mixing interference images on the oscilloscope. However, the laser light intensity can also be measured by the photoelectric detector, and the spectrograph displays the corresponding spectrum as shown in **Figure 7**. Due to the high zero noise power of the instrument, it is unable to display the low frequency noise part. The self-mixing signal diagram in the figure shows that the driving frequency is 100 Hz, the peak driving voltage is 6 V, and the corresponding piezoelectric ceramic amplitude is 288 nm. This is due to the additional loss and dispersion effect in the external optical fiber, which limits the measurement range of remote microvibration sensing.

4. Discussing

By pasting reflective surfaces with different reflectivity (including mirror, reflective film and white paper) on the PZT surface, a series of self-mixing interference signals with different feedback intensities can be obtained, as shown in **Figure 8**. To highlight the effect of feedback coefficient *C*, the output power of the laser is redefined as:

$$P_{out} = P_0\left(1 + m\cos\varphi(t)\right) \tag{7}$$

$$m = \tau_1 C \frac{1}{\tau\left(1 - r_2^2\right)\log\left(r_1 r_2\right)\sqrt{1-\alpha^2}} \tag{8}$$

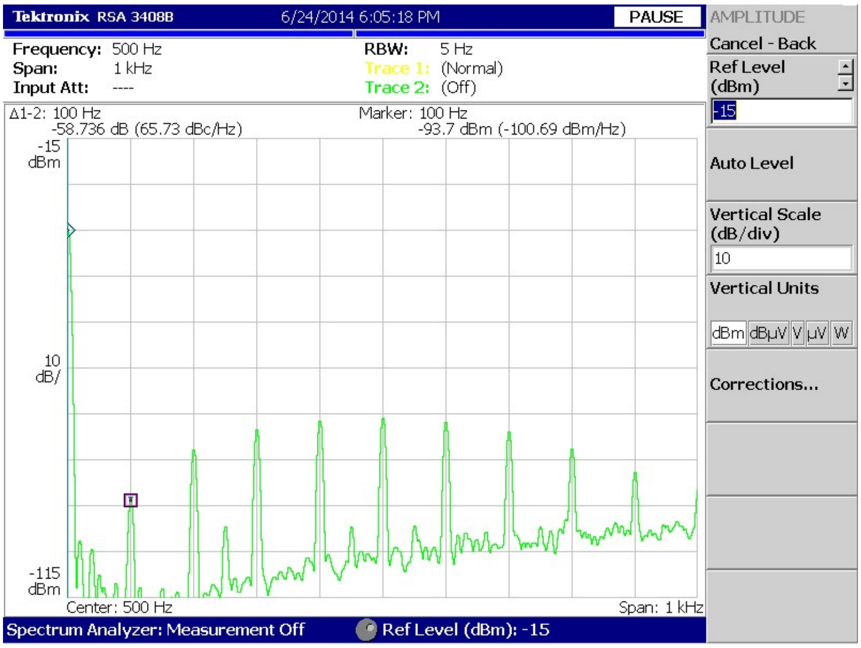

Figure 9. Self-mixing interference signals with the 20 km SMF.

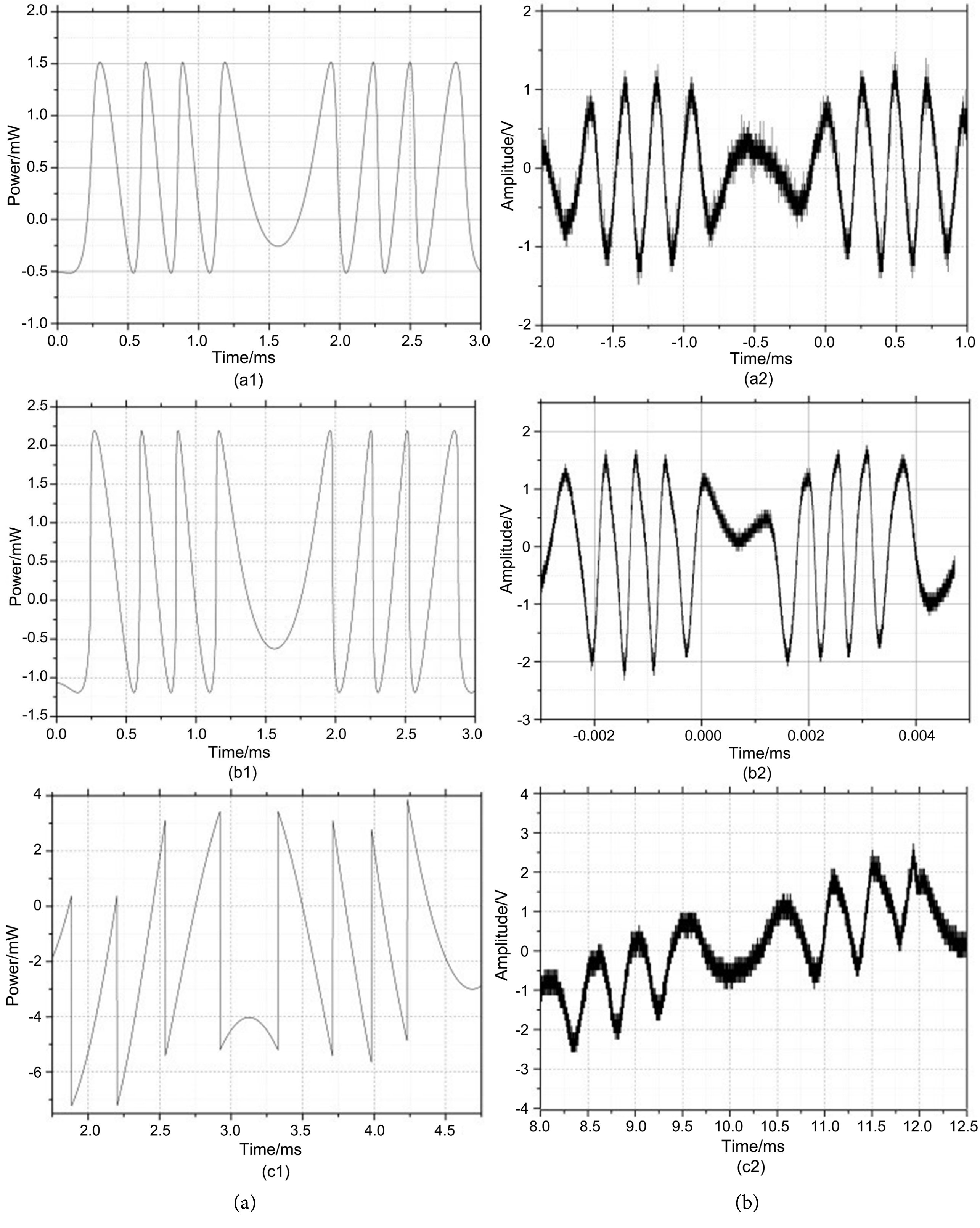

Figure 10. Simulation diagram and experimental diagram of self-mixing interference signal under different feedback intensity. (a) Analog signal diagram; (b) Signal diagram measured in experiment. (a1) $C = 0.6$; (a2) The reflector used in the figure is white paper; (b1) $C = 1.0$; (b2) The reflective surface used in the figure is a reflective film; (c1) $C = 5.0$; (c2) The reflector used in the figure is a mirror.

$$C = \eta \frac{\tau_1}{\tau}\left(1 - r_2^2\right)\frac{r_3}{r_2}\sqrt{1+\alpha^2} \tag{9}$$

where P_{out} represents the actual output power of the laser, P_0 represents the output power of the laser without feedback, and m represents the modulation coefficient, $\tau_1 = 2L_{in}/c$ represents the time required for photons to travel back and forth in the cavity for one week. And α is the linewidth broadening factor.

The left column of **Figure 10** shows the simulated self-mixing interference signal diagram under different feedback coefficients ((a1) $C = 0.6$, (b1) $C = 1.0$, (c1) $C = 5.0$). The target driving signal is set at 1500 nm and 320 Hz is unchanged. The figure on the right is the corresponding experimental figure: (a2) The reflector used in the figure is white paper; (b2) The reflective surface used in the figure is a reflective film; (c2) The reflector used in the figure is a mirror.

$1 < C < 4.6$ is a moderate feedback interval, and $C > 4.6$ is a strong feedback interval. In the previous research on semiconductor lasers, linear cavity fiber lasers, ring cavity fiber lasers and other lasers, these intervals are defined as the intervals that cannot be used to study self-mixing signals using the number stripe method. When $C > 1$, the external cavity mode oscillation causes the laser to output multimode laser, the self-mixing signal will be distorted, and finally the fringes in the interference signal will be missing [16].

However, in our self-mixing microvibration measurement system using an all fiber distributed feedback laser, the number stripe method can still be used to study the self-mixing signal in the strong feedback interval. Because the self-mixing signal graph obtained by our system shows signal distortion, but the number of stripes does not change. This is because the all fiber distributed feedback laser has an extremely short internal cavity (5 cm), which can achieve the output of a single-mode laser, thus avoiding the loss of stripes caused by mode hopping in the strong feedback region.

The adjusting range of PZT driving voltage used in the experiment is limited, which affects the value range of vibration signal amplitude. It is necessary to optimize the experimental system to achieve higher precision microvibration measurement. Meanwhile, the change value of the length of the external optical fiber is small, and further research is needed to determine the measuring range of the system.

5. Conclusions

In this paper, a theoretical analysis and the comparison with the experimental results on the self-mixing vibration measurement system with DFBFL were presented.

From the comparison, the following conclusions can be deduced.

1) The experimental results showed a good agreement with the theoretical analysis.

2) The compact structure and higher sensitivity SMI remote sensors can be got by DFB fiber laser.

3) The experiment shows the feasibility of DFB fiber laser for remote measurement up to 20 km of the displacement and the vibration.

In conclusion, the self-mixing microvibration measurement system based on all fiber distributed feedback fiber laser was analyzed and introduced theoretically and experimentally. The experimental and simulation results show that the minimum amplitude that can be measured by the self-mixing microvibration measurement system designed by us is 70 nm. It is predicted that our system can detect vibration with smaller amplitude and longer distance. This compact self-mixing microvibration measurement system provides a better choice for microvibration measurement because of its high sensitivity, simple structure and low cost.

In further researches, optimization of experimental system is intended to ameliorate measurement resolution, and improvements are under way.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] King, P.G.R. and Steward, G.J. (1963) Metrology with an Optical Maser. *New Scientist*, **17**, 180-182.

[2] Zhang, Z., *et al.* (2020) Vibration Measurement Based on the Local Maximum Detection Algorithm for Laser Self-Mixing Interferometry. *IEEE Access*, **8**, 63462-63469. https://doi.org/10.1109/ACCESS.2020.2984282

[3] Jiang, C., *et al.* (2019) Rotation Velocity Measurement Based on Self-Mixing Interference with a Dual-External-Cavity Single-Laser Diode. *Applied Optics*, **58**, 604-608. https://doi.org/10.1364/AO.58.000604

[4] Zhu, K., *et al.* (2017) Single-Spot Two-Dimensional Displacement Measurement Based on Self-Mixing Interferometry. *Optica*, **4**, 729-735. https://doi.org/10.1364/OPTICA.4.000729

[5] Veng, M., *et al.* (2019) Fringe Disappearance in Self-Mixing Interferometry Laser Sensors: Model and Application to the Absolute Distance Measurement Scheme. *IEEE Sensors Journal*, **19**, 5521-5528. https://doi.org/10.1109/JSEN.2019.2901125

[6] Sudo, S., *et al.* (2007) Detection of Small Particles in Fluid Flow Using a Self-Mixing Laser. *Optics Express*, **15**, 8135-8145. https://doi.org/10.1364/OE.15.008135

[7] Lu, L., *et al.* (2011) Study on Self-Mixing Interference Using Er^{3+}-Yb^{3+} Codoped Distributed Bragg Reflector Fiber Laser with Different Pump Power Current. *Optics Communications*, **284**, 5781-5785. https://doi.org/10.1016/j.optcom.2011.08.065

[8] Lu, L., *et al.* (2012) Self-Mixing Signal in Er^{3+}-Yb^{3+} Codoped Distributed Bragg Reflector Fiber Laser for Remote Sensing Applications up to 20 Km. *IEEE Photonics Technology Letters*, **24**, 392-394. https://doi.org/10.1109/LPT.2011.2179922

[9] Wang, W.M., *et al.* (1994) Self-Mixing Interference inside a Single-Mode Diode Laser for Optical Sensing Applications. *Journal of Lightwave Technology*, **12**, 1577-1587. https://doi.org/10.1109/50.320940

[10] Dandridge, A., Tveten, A.B. and Giallorenzi, T.G. (1982) Homodyne Demodulation Scheme for Fiber Optic Sensors Using Phase Generated Carrier. *IEEE Transactions on Microwave Theory and Techniques*, **30**, 1635-1641. https://doi.org/10.1109/TMTT.1982.1131302

[11] Otsuka, K. (1994) Ultrahigh Sensitivity Laser Doppler Velocimetry with a Microchip Solid-State Laser. *Applied Optics*, **33**, 1111-1114. https://doi.org/10.1364/AO.33.001111

[12] Yelen, K., Hickey, L. and Zervas, M.N. (2003) A New Design Approach for DFB Lasers for Improved Efficiency. *OSA*, **140**, 3490.

[13] Kurkov, A.S., *et al.* (1997) Application of π/2 Phase Shifted Bragg Grating for the Longitudinal Mode Selection of Single-Frequency Fibre Lasers. 11*th International Conference on Integrated Optics and Optical Fibre Communications*. 23*rd European Conference on Optical Communications IOOC-ECOC*97, Edinburgh, 22-25 September 1997. https://doi.org/10.1049/cp:19971579

[14] Schulzgen, A., *et al.* (2008) Distributed Feedback Fiber Laser Pumped by Multimode Laser Diodes. *Optics Letters*, **33**, 614-646. https://doi.org/10.1364/OL.33.000614

[15] Du, Z.T., Lu, L. and Zhang, W.H. (2013) High-Accuracy Fiber Optical Microphone in a DBR Fiber Laser Based on a Nanothick Silver Diaphragm by Self-Mixing Technique. *OE*, **21**, 30580-30590. https://doi.org/10.1364/OE.21.030580

[16] Yu, Y., *et al.* (2009) Optical Feedback Self-Mixing Interferometry with a Large Feedback Factor C: Behavior Studies. *IEEE Journal of Quantum Electronics*, **45**, 840-848. https://doi.org/10.1109/JQE.2009.2013153