PHOTONIC SENSORS / Vol. 7, No. 3, 2017: 206–210

Low-Frequency Vibration Measurement by a Dual-Frequency DBR Fiber Laser

Bing ZHANG, Linghao CHENG*, Yizhi LIANG, Long JIN, Tuan GUO, and Bai-Ou GUAN

Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou, 510632, China

*Corresponding author: Linghao CHENG E-mail: chenglh@ieee.org

Abstract: A dual-frequency distributed Bragg reflector (DBR) fiber laser based sensor is demonstrated for low-frequency vibration measurement through the Doppler effect. The response of the proposed sensor is quite linear and is much higher than that of a conventional accelerometer. The proposed sensor can work down to 1 Hz with high sensitivity. Therefore, the proposed sensor is very efficient in low-frequency vibration measurement.

Keywords: Fiber laser sensors; Doppler effect; vibration measurement

Citation: Bing ZHANG, Linghao CHENG, Yizhi LIANG, Long JIN, Tuan GUO, and Bai-Ou GUAN, "Low-Frequency Vibration Measurement by a Dual-Frequency DBR Fiber Laser," *Photonic Sensors*, 2017, 7(3): 206–210.

1. Introduction

Vibration measurement is widely employed in many applications, such as aerospace, architectural, automotive, security, and medical applications [1–4]. Frequently, vibration can be measured by measuring the acceleration of the target through attaching an accelerometer onto the target surface [5–6]. However, for many applications, the surface of the target may be difficult to be accessed, or may be too small or too hot to be attached a physical transducer. For these applications, non-contact measurement is highly demanded [7–8].

Doppler effect based vibration measurement is one method capable of measuring vibration without attaching transducer onto targets [9–12]. Moreover, it is quite efficient in measurement of vibration at low frequency at which conventional accelerometers are highly inefficient. Lasers are frequently employed in this method by directing a laser beam onto the target surface and measuring the frequency variation of the reflected laser beam due to the Doppler effect resulted from the vibration. Among various lasers, fiber lasers are popular in vibration measurement for their light weight and compact size.

In this paper, we propose a low-frequency vibration measurement scheme based on the Doppler effect by employing a dual-frequency distributed Bragg reflector (DBR) fiber laser [13]. With dual-frequency output of the fiber laser, the scheme works in a heterodyne regime without employing a frequency shifter and hence results in a very compact design. The proposed sensor can work down to 1 Hz with high sensitivity and linear response.

Received: 9 January 2017 / Revised: 10 March 2017

DOI: 10.1007/s13320-017-0402-8
Article type: Regular

2. Theory and experiment

The proposed scheme is shown in Fig. 1, which is based on a distributed Bragg reflector (DBR) fiber laser inscribed on an Er/Yb co-doped fiber by a 193-nm excimer [14]. The output power of the dual-frequency DBR laser is about –21 dBm, and the beat note power is about –10 dBm. The laser is composed of one 5-mm grating and one 5.5-mm grating, spaced in about 1 mm. Pumped at 980 nm, the laser outputs two wavelengths at 1531 nm with orthogonal polarizations and a frequency difference of about 3.256 GHz due to the intra-cavity birefringence. After being amplified by an erbium-doped fiber amplifier (EDFA), the two orthogonally polarized outputs are separated by a polarization beam splitter (PBS). One of the two polarizations is directed to a vibrating surface by a collimator, and the reflected light from the surface is collected by the collimator and combined after amplification with the other polarization through a circulator. The resulted light is then detected by a photo-detector, and the generated signal is sampled and processed to recover the vibration signal.

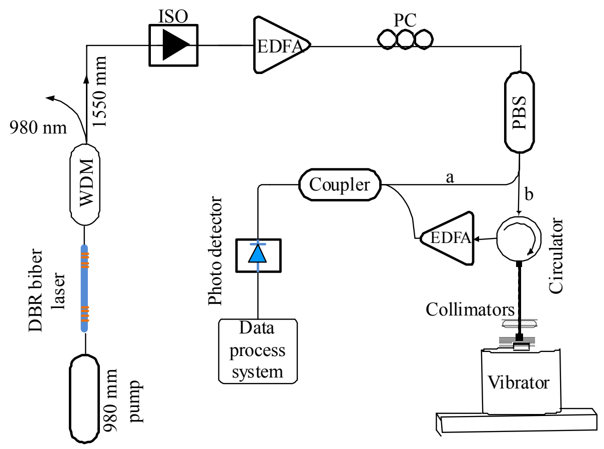

Fig. 1 Experimental setup: WDM: wavelength division multiplexer; ISO: isolator; EDFA: erbium-doped fiber amplifier; PC: polarization controller; PBS: polarization beam splitter.

The vibration is generated by a vibrator. Due to the Doppler effect, the vibrating surface induces a frequency shift to the light focused on the surface. This frequency shift is proportional to the vibration velocity. Therefore, the reflected light can be expressed as

$$r_0(t) \propto \exp\left[j\omega_0 t + j\frac{\omega_0}{c}\int_0^t v(\tau)d\tau + j\theta_0(t) \right] \quad (1)$$

where ω_0 and θ_0 are the original angular frequency and the initial phase of the reflected light with phase noise included, respectively, and v is the vibration velocity. When the combined light of the reflected light and the other polarization light is photo-detected, the resulted photo-electrical current is written as

$$I(t) \propto \exp\left[j\Delta\omega t + j\frac{\omega_0}{c}\int_0^t v(\tau)d\tau + j\Delta\theta(t) \right] \quad (2)$$

where $\Delta\omega$ and $\Delta\theta$ are the frequency difference and the initial phase difference between the two polarizations. Through frequency demodulation, the instantaneous frequency of the photo-electrical current is obtained as

$$\omega(t) = \Delta\omega + \frac{\omega_0}{c}v(t) + \frac{d\Delta\theta(t)}{dt} \quad (3)$$

from which the vibration velocity can be obtained through filtering. Note that the last term in (3) results in some measurement error because the phase noise of the laser is also converted to frequency variation through frequency demodulation. However, majority of this noise can be filtered out by a properly designed filter. Frequently, vibration is also measured through acceleration, which can also be obtained through (3) by taking differential:

$$a(t) = \frac{d\omega(t)}{dt} = \frac{\omega_0}{c}\frac{dv(t)}{dt} + \frac{d^2\Delta\theta(t)}{dt^2}. \quad (4)$$

Figure 2 shows a measurement for a vibration at 20 Hz. The vibrator is driven at 0.8 V. The spectrum clearly shows the vibration signal at 20 Hz with a signal-to-noise ratio (SNR) of about 40 dB. It then shows that the proposed scheme works very well at low frequency. Equation (4) shows that at the same level of acceleration, the response of the proposed scheme will be vibration frequency dependent due to the differential of the velocity. Therefore, the response of the proposed scheme will be higher at lower frequency and lower at higher frequency for the same level of acceleration.

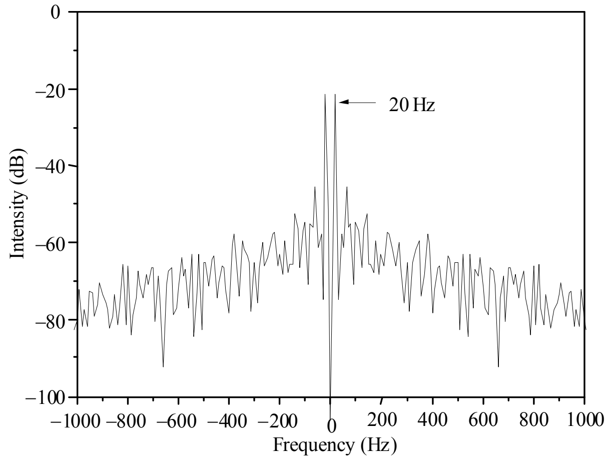

Fig. 2 Measured spectrum for a vibration at 20 H (the driving voltage of the vibrator is 0.8 V).

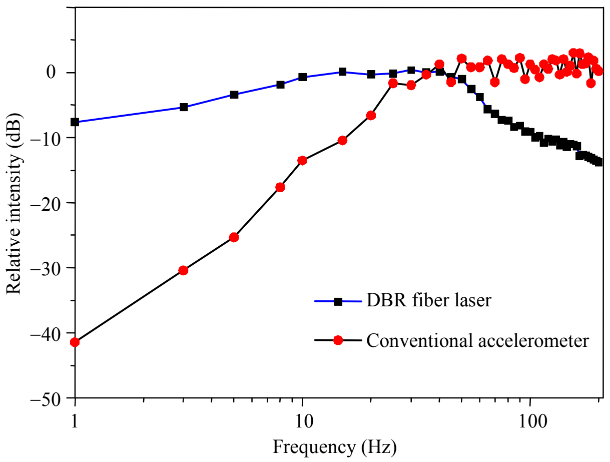

Fig. 3 Measured response at various vibrating frequencies for the DBR fiber laser based measurement and a conventional accelerometer based measurement.

Figure 3 shows the measured response at various frequencies. For comparison, the measured response of a conventional accelerometer is also plotted. The two response curves are normalized to their responses at 35 Hz, respectively. It then shows that the response of the proposed scheme by the DBR fiber laser is higher at lower frequency while the response of the conventional accelerometer degrades heavily at low frequency although this degradation may be the combined response degradation of the conventional accelerometer and the vibrator at low frequency. The proposed scheme works very well down to 1 Hz. Actually, the scheme can work at even lower vibrating frequency. However, the memory size of the data acquisition unit limits the measurement to 1 Hz.

Figure 4 shows the response of the proposed scheme relative to that of the conventional accelerometer based scheme. The frequency dependent response of the vibrator is then removed from the curve. The curve shows a tendency basically proportional to $1/\omega^2$ which is shown as a linear curve in log-log plot. For the proposed scheme based on the Doppler effect, the direct measured is velocity, while for the accelerometer, it is acceleration. Because acceleration is the differential of velocity, the ratio between the velocity and acceleration is proportional to $1/\omega$ in frequency domain. With the vertical scale in decibels, $1/\omega^2$ is therefore resulted as shown by the dash curve for fitting according to $1/\omega^2$ in Fig. 4. The slope of the curve is the theoretical value, that is, –20 dB/decade. However, the best fitting of the measured results is by $1/\omega^{2.2}$ as shown by the solid curve with a slope of –22 dB/decade in Fig. 4. It then shows that the accelerometer has higher gain at high frequencies, which confirms again that the proposed scheme works better in low frequency in which the conventional accelerometer is quite inefficient.

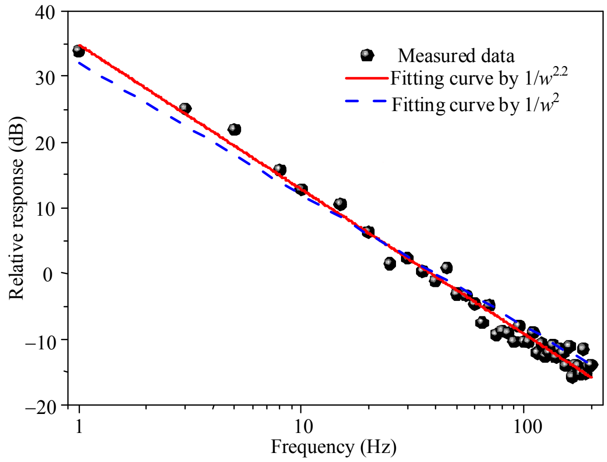

Fig. 4 Response of the proposed scheme relative to that of the conventional accelerometer based scheme.

Figure 5 shows the response of the proposed scheme at various driving levels of the vibrator. A quite linear curve is observed. Actually, the deviation of the measured data from the linear curve should be largely attributed to the non-uniform response of the vibrator at various driving voltages because the proposed scheme is a non-contact measurement.

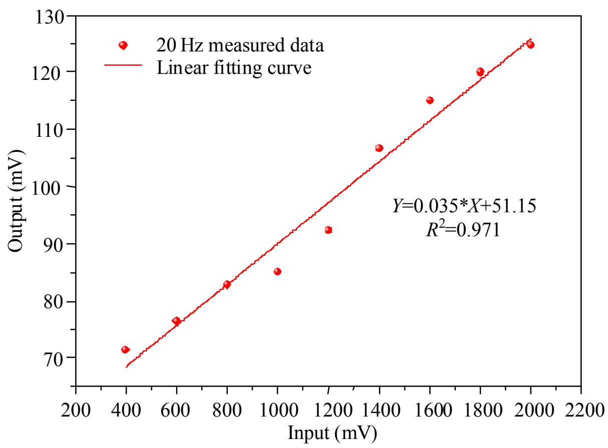

Fig. 5 Measured response at various driving voltages of the vibrator for a vibrating frequency of 20 Hz.

3. Conclusions

Based on the Doppler effect, a fiber-optic vibration measurement scheme is proposed and demonstrated by utilizing a dual-frequency DBR fiber laser, which results in a compact scheme due to the miniature dimensions of the fiber laser. The scheme demonstrates a linear response and high sensitivity at low frequency in which conventional accelerometers are quite inefficient. The scheme works very well in the band below 200 Hz and can works down to 1 Hz. Therefore, the proposed scheme is very useful for low-frequency vibration measurement.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11474133 and 61235005), Natural Science Foundation of Guangdong Province of China (No. 2014A030310419), and the Guangzhou Key Collaborative Innovation Foundation of China (No. 2016201604030084).

References

[1] E. Reithmeier, S. Mirzaei, and N. Kasyanenko, “Optical vibration and deviation measurement of rotating machine parts,” *Optoelectronics Letters*, 2008, 4(1): 45–48.

[2] S. Wang, X. Fa, and Q. Liu, “Distributed fiber-optic vibration sensing based on phase extraction from time-gated digital OFDR,” *Optics Express*, 2015, 23(26): 33301–33309.

[3] A. Wada, S. Tanaka, and N. Takahash, “Multipoint vibration sensing using fiber Bragg gratings and current-modulated laser diodes,” *Journal of Lightwave Technology*, 2016, 34(19): 4610–4614.

[4] D. Jiang and H. Wei, “Review of applications for fiber Bragg grating sensor,” *Journal of Optoelectronics Laser*, 2002, 13(4): 420–430.

[5] R. P. Linessio, K. D. Sousa, T. D. Silva, C. A. Bavastri, P. F. D. C. Antunes, and J. C. C. D. Silva, “Induction motors vibration monitoring using a biaxial optical fiber accelerometer,” *IEEE Sensors Journal*, 2016, 16(22): 8075–8082.

[6] Y. Weng, X. Qiao, Z. Feng, M. Hu, J. Zhang, and Y. Yang, “Compact FBG diaphragm accelerometer based on L-shaped rigid cantilever beam,” *Chinese Optics Letters*, 2011, 9(10): 22–25.

[7] C. R. Farrar, T. W. Darling, A. Migliori, and W. E. Baker, “Microwave interferometers for non-contact vibration measurements on large structures,” *Mechanical Systems and Signal Processing*, 1999, 13(2): 241–253.

[8] T. Li, Y. Tan, Z. Zhou, L. Cai, S. Liu, Z. He, *et al.*, “Study on the non-contact FBG vibration sensor and its application,” *Photonic Sensors*, 2015, 5(2):128–136.

[9] K. M. Singh and P. Sumathi, “Synchronization technique for Doppler signal extraction in ultrasonic vibration measurement systems,” *IEEE Transactions on Instrumentation and Measurement*, 2015, 64(12):

3162–3172.

[10] J. H. Zhou, G. Chen, and Q. S. Cao, "Design of ultrasonic system for vibration measurement based on Doppler effect," *Instrument Technique and Sensor*, 2015, 1(7): 61–62.

[11] P. Castellini, M. Martarell, and E. P. Tomasini, "Laser doppler vibrometry: development of advanced solutions answering to technology's needs," *Mechanical Systems and Signal Processing*, 2006, 20(6): 1265–1285.

[12] Z. Y. Kuang, L. H. Cheng, B. O. Guan, H. Liang, and B. Guan, "Dual-polarization fiber grating laser-based laser Doppler velocimeter," *Chinese Optical Letter*, 2016, 14(5): 050602–050605.

[13] Y. Zhang, B. O. Guan, and H. Y. Tam, "Ultra-short distributed Bragg reflector fiber laser for sensing application," *Optics Express*, 2009, 17(12): 10050–10055.

[14] Y. Z. Liang, L. Jin, L. H. Cheng, and B. O. Guan, "Stabilization of microwave signal generated by a dual-polarization DBR fiber laser via optical feedback," *Optics Express*, 2014, 22(24): 29356–29362.