Wang, Jianfei and Flockhart, Gordon M. H. and Uttamchandani, Deepak (2018) Effects of laser intensity noise on polarimetric distributed feedback fibre laser ultrasonic sensor. In: The 26th International Conference on Optical Fibre Sensors, 2018-09-24 - 2018-09-28, SwissTech Convention Center, EPFL Campus. ,

Effects of Laser Intensity Noise on Polarimetric Distributed Feedback Fibre Laser Ultrasonic Sensor

Jianfei Wang*[1,2], Gordon M. H. Flockhart[2], Deepak Uttamchandani[2]
[1]College of Meteorology & Oceanology, National University of Defense Technology, Changsha 410073, China
[2]Centre for Microsystems & Photonics, Department of Electronic & Electrical Engineering, University of Strathclyde, 204 George Street, Glasgow, G1 1XW, UK

Corresponding author: wjfjoy@126.com

Abstract: The influence of the relative intensity noise, in particular the relaxation oscillation noise, of a distributed feedback (DFB) fibre laser on the performance of a polarimetric DFB fibre laser ultrasonic sensor is investigated theoretically and experimentally. A novel demodulation algorithm for the DFB fibre laser ultrasonic sensor is used to demodulate the polarization beat frequency and eliminate the effects of the intensity noise completely. The sensing system is demonstrated to demodulate time varying ultrasonic signals at 2.25 MHz and 10 MHz.
OCIS codes: (280.0280)

1. Introduction

Polarimetric heterodyning fibre grating laser ultrasonic sensors, with outstanding characteristics of high sensitivity, compact size and broad bandwidth, have received great interest due to their potential application in biomedical photoacoustic imaging [1,2]. The operating principle of this type of ultrasonic sensor is based on frequency modulation of the beat signal from two orthogonal polarization lasing modes of a fibre grating laser with single-longitudinal mode operation. When the fibre laser ultrasonic sensor is subjected to an ultrasonic field, the acoustic pressure will induce different periodic index changes along and perpendicular to the propagation direction of ultrasonic wave [3]. Therefore, the ultrasound changes the fibre birefringence and the beat frequency of the fibre laser is modulated.

Fundamental characteristics of the polarimetric heterodyning fibre grating laser ultrasonic sensor, such as high sensitivity, linear response, and bandwidth, have been demonstrated previously [4-6]. The relative intensity noise (RIN) and relaxation oscillation are two main characteristics of the fibre grating laser, influencing the performance of the ultrasonic sensor. In addition, the interrogation methods are also an important part of the fibre laser ultrasonic sensor system.

In this paper, the influence of the RIN of the DFB fibre laser on the polarimetric DFB fibre laser ultrasonic sensor is investigated theoretically and experimentally. The RIN noise peak due to the laser's relaxation oscillation is observed to frequency modulate the polarization beat frequency therebyintroducing an unwanted signal and potentially limiting the low-frequency ultrasound measurement range. To mitigate this cross-talk, a novel demodulation algorithm of the DFB fibre ultrasonic sensor with stable output is presented. The results of this research can also be applied to the polarimetric heterodyning ultrasonic sensor based on distributed Bragg reflector (DBR) fibre lasers.

2. Theory

To simplify the analysis, we treated the intensity noise due to the relaxation oscillation of the DFB fibre laser as a single frequency signal. The total intensity noise of the DFB fibre laser can be treated as the superposition of multiple single noise signals. Then two orthogonal polarization modes of the DFB fibre laser can by expressed by

$$E_{x,y} = A_{x,y}(1 + k_n \cos \omega_n t)\cos(\omega_{x,y} t + \varphi_{x,y}) \quad (1)$$

where k_n ($k_n \ll 1$) and ω_n are amplitude and angular frequency of the intensity noise signal of the DFB fibre laser respectively. $A_{x,y}$, $\omega_{x,y}$ and $\varphi_{x,y}$ are the amplitude, angular frequency and phase of the two orthogonal polarization modes respectively.

Assuming A_x=A_y=A, then, the intensity of the beat signal received by a photodetector can be written as

$$I \approx A^2\{1 + 2k_n\cos\omega_n + \cos(\Delta\omega t + \Delta\varphi) + k_n\cos[(\Delta\omega + \omega_n)t + \Delta\varphi] + k_n\cos[(\Delta\omega - \omega_n)t + \Delta\varphi]\} \quad (2)$$

where we ignore the extremely high frequency of $2\omega_x$, $2\omega_y$ and $\omega_x + \omega_y$, and the higher order terms of k_n are also neglected.

Equation (2) indicates that the beat signal of the two orthogonal polarization modes contains four frequency components: intensity noise frequency (ω_n), beat frequency ($\Delta\omega$) and a pair of sidebands of the beat frequency

$(\Delta\omega + \omega_n, \Delta\omega - \omega_n)$. It should be noted that this pair of sidebands is caused by intensity noise, not by the ultrasonic signals of interest.

In order to obtain the time varying waveforms of the ultrasonic signals and eliminate the influence of the laser intensity noise, an in-phase and quadrature (I/Q) demodulation algorithm was applied. Figure 1 shows the flow diagram of the I/Q quadrature demodulation method. By dividing two quadrature signal components, the intensity noise of the DFB fibre laser is eliminated in principle.

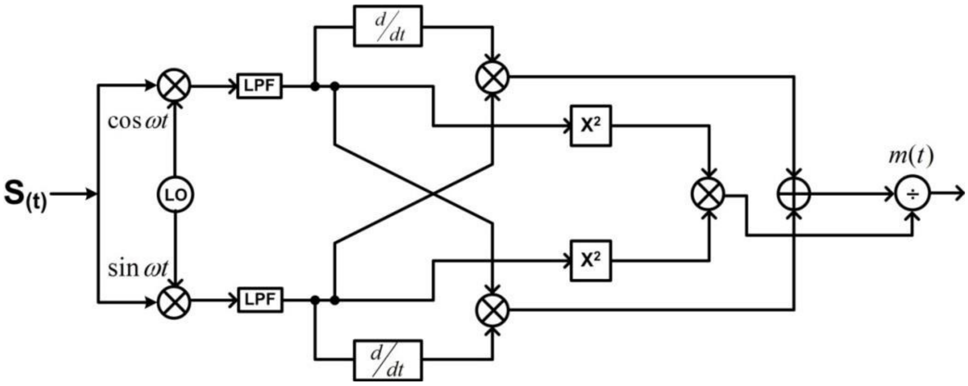


Fig. 1. Flow diagram of the I/Q quadrature demodulation algorithm.

3. Experimental setup

The experimental setup is shown in Fig. 2. The DFB fibre laser was pumped by a 980 nm laser diode through a 980/1550 nm wavelength division multiplexer (WDM). An optical isolater was placed at the laser output to eliminate unwanted reflections. A polarization controller was used to optimally align the orthogonal polarization modes of the DFB laser at 45° to the transmission axis of an in-line fibre polarizer. The transmitted optical components generated a beat frequency when detected using a high-speed (3 GHz) photodetector (LBR-10M3G-10-15-10). The detected beat signal was measured by an electrical spectrum analyzer (Agilent, E4404b) or the proposed demodulation system, which consists of a high-speed acquisition card and a computer.

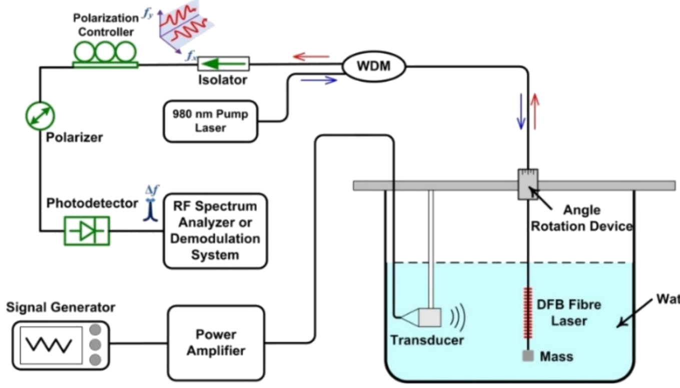


Fig. 2. Schematic diagram of the experimental setup.

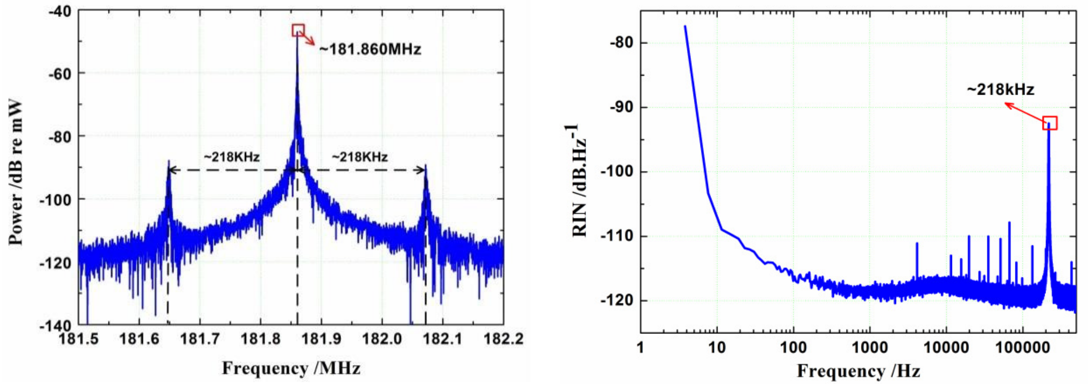
The DFB fibre laser ultrasonic sensor was located in the far field of either a planar 2.25 MHz (Olympus i8-0216-S) or a planar 10 MHz (Olympus Panametrics A315S) immersion ultrasonic transducer in a water tank. An arbitrary waveform generator was used to produce a periodic voltage waveform. A continuous wave sinusoid and a 6 cycle Hamming windowed tone burst were the waveforms used. The arbitrary waveform generator's output was amplified by an RF power amplifier (ENI 2100L) to drive the transducers and generate ultrasound in the water. A small weight was attached to the end of the DFB fibre laser to keep the fibre straight.

4. Results and discussions

4.1 Beat signal and sidebands

Initially the high-speed photodetector was connected to an oscilloscope for measuring the beat signal of the DFB fibre laser. No driving voltage was applied to the ultrasonic transducer.

Figure 3(a) shows the beat signal spectrum of the DFB fibre laser at a pump laser driving current of 150 mA. The frequency of the beat signal is ~182 MHz; however it isobserved that there is a pair of symmetrical sidebands near the beat frequency, and the frequency separation is ~218 kHz. The theoretical analysis in equation (2) indicates that the intensity noise of the DFB fibre laser can induce sidebands of the polarization beat signal. The relative intensity noise of the DFB fibre laser at the same pump laser driving current was measured and shown in Fig. 3(b). The relaxation oscillation frequency of the DFB fibre laser was measured to be 218 kHz. The results show an excellent agreement between the observed frequency spacing of the sidebands on the polarization beat frequency signal and the frequency of the relaxation oscillation noise peak in the RIN spectrum. From the measurement results shown in Fig. 3, one can find that the intensity noise (relaxation oscillation) of the DFB fibre laser will induce a pair of sidebands on the beat frequency.



(a) (b)

Fig. 3. Polarization beat signal spectra (a) and RIN (b) of the DFB fibre laser at pump laser driving current of 150 mA.

Figure 4 shows the beat signal spectrum recorded by the spectrum analyzer when the ultrasonic transducer was driven by a continuous wave signal at frequency of 2.25 MHz. As expected, the beat signal was frequency modulated by the ultrasonic signal as shown by the visible sidebands at 2.25 MHz from the beat signal. Theoretical analysis and the experimental results shown in Fig. 4, confirm that ultrasonic signals and the intensity noise of the DFB fibre laser will both induce sidebands of the beat signal of the DFB fibre laser ultrasonic sensor. Therefore, in practical applications, we must carefully discriminate between the true ultrasonic signals and the intensity noise, as cross-talk from the intensity noise could potentially interfere with low-frequency ultrasound signals.

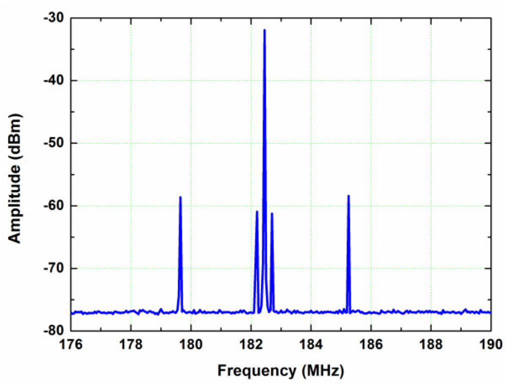
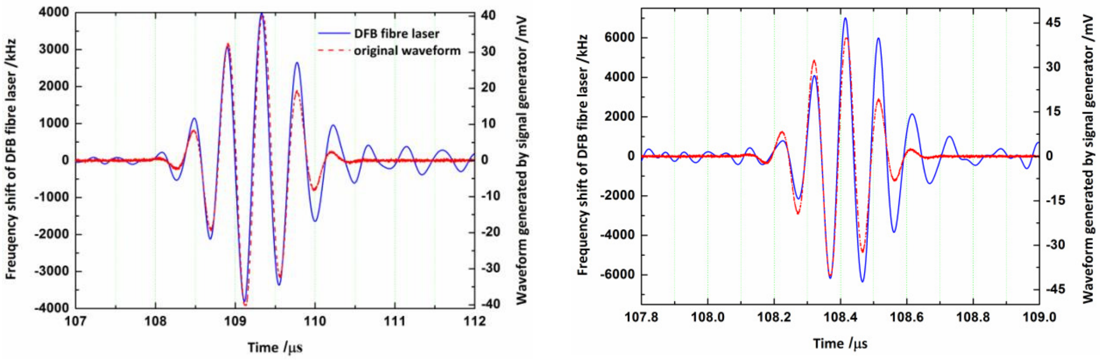


Fig. 4. Beat signal spectrum of the DFB fibre laser as the acoustic transducer was driven in 2.25MHz continuous signal.

4.2. Ultrasonic Signal Demodulation

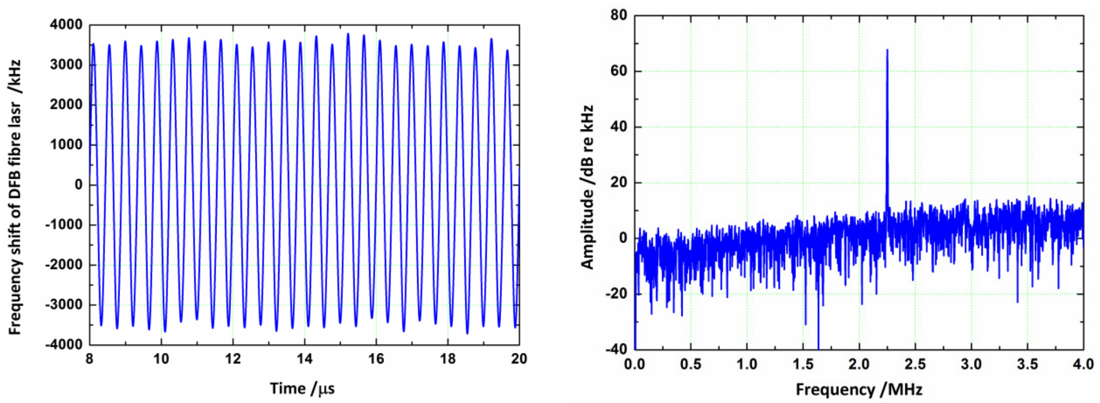
To measure time varying ultrasonic signals, the orthogonal laser modes were incident on a high-speed photodetector resulting in the polarization beat frequency which was recorded by a high-speed acquisition card. The ultrasonic signal was subsequently demodulated through an interrogation program in a PC.

Figure 5 shows the output signals (blue line) of the DFB fibre laser ultrasonic sensor at 2.25 MHz and 10 MHz. The original waveforms (red dash line) of the signal generator output, which were monitored by an oscilloscope, are superimposed for comparison. It should be noted that the time axis of the original waveforms in Fig. 5 has been shifted in order to remove the acoustic propagation delay and facilitate a better comparison with the output waveforms detected by the DFB fibre laser sensor. The exact starting time of the original waveforms is zero. The detected ultrasonic waveform is in good agreement with the original input waveform but shows some additional oscillations after the tone burst. We believe that these are due to acoustic resonances in the fibre coating. It is clear that, the DFB fibre laser sensor provides a near ideal waveform of ultrasound with high signal quality, and the I/Q quadrature demodulation can demodulate the ultrasonic signal.



(a) (b)

Fig. 5. Six-cycle tone burst signal detected by DFB fibre laser ultrasonic sensor comparing with original waveform generated by signal generator at different frequencies. (a) 2.25 MHz, (b) 10 MHz.



(a) (b)

Fig. 6. Demodulated 10 MHz continuous signal. (a) Time domain. (b) Frequency domain.

Figure 6(a) shows the demodulated signal of the DFB fibre laser ultrasonic sensor when the transducer was driven by continuous signal at frequency of 2.25 MHz. Figure 6(b) is the FFT of the demodulated ultrasonic signal shown in Fig 6(a). We can only observe the 2.25 MHz ultrasonic signal spectrum in Fig. 6(b), and the relaxation oscillation noise signal of the DFB fibre laser at frequency of 218 kHz was eliminated. This indicates the I/Q demodulation method can, in principle, eliminate the influence of the DFB fibre laser intensity noise.

5. Conclusions

We have studied the influences of the intensity noise of the DFB fibre laser on the polarimetric DFB fibre laser ultrasonic sensor. Our theoretical analysis and experimental results both indicate that the intensity noise of the DFB fibre laser and the ultrasonic signal will induce sidebands of the beat signal of the DFB fibre laser ultrasonic sensor. Therefore, we must distinguish the true ultrasonic signals and the intensity noise carefully when we use sidebands to determine the ultrasonic signal. Moreover, I/Q quadrature demodulation algorithm was used to demodulate time varying ultrasonic signals of the DFB fibre laser ultrasonic sensor. This demodulation method can eliminate the effects of intensity noise of the DFB fibre laser in principle, presenting a great advantage in the practical applications of the polarimetric fibre laser ultrasonic sensor.

References

[1] Y. Liang, L. Jin, L. Wang, X. Bai, L. Cheng and B. O. Guan. "Fiber-laser-based ultrasound sensor for photoacoustic imaging," Scientific Reports DOI: 10.1038/srep40849 (2017).

[2] D. Liu, Y. Liang, L. Jin, H. Sun, L. Cheng and B. O. Guan. "Highly sensitive fiber laser ultrasound hydrophones for sensing and imaging applications," Optics Lett. 41(9), 4530-4533 (2016).

[3] L. Flax, J. H. Cole, R. P. De Paula, and J. A. Bucaro, "Acoustically induced birefringence in optical fibers," J. Opt. Soc. Am. 72(9), 1159–1162 (1982).

[4] B. O. Guan, H. Y. Tam, S. T. Lau, and H. L. W. Chan, "Ultrasonic hydrophone based on distributed Bragg reflection fiber laser," IEEE Photon. Technol. Lett. 16(1), 169-171 (2005).

[5] S. T. Lau, L. Y. Shao, H. L. W. Chan, H. Y. Tam, C. H. Hu, H. H. Kim, R. Liu, Q. Zhou and K. K. Shung. "Characterization of a 40-MH focused transducer with a fiber grating laser hydrophone," IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 56(12), 2714-2718 (2009).

[6] T. Guo, A. C. L. Wong, W. S. Liu, B. O. Guan, C. Lu and H. Y. Tam. "Beat-frequency adjustable Er^{3+}-doped DBR fiber laser for ultrasound detection," Optics Express 19(3), 2485-2492 (2011).