Optics Letters

Quadrature detection for self-mixing interferometry

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Received 1 March 2018; revised 3 April 2018; accepted 3 April 2018; posted 3 April 2018 (Doc. ID 324878); published 27 April 2018

We establish a new quadrature detection system for self-mixing interferometry using two photodiodes and a 22.5-deg rotated beam splitter. The method is based on a rotating beam splitter placed between the laser diode and the measured object, and two quadrature self-mixing signals can be obtained. Then, an arctangent phase algorithm can be used to demodulate the quadrature signal to acquire the object vibration information. This method simplifies the self-mixing signal demodulation process and allows us to demodulate the vibrating displacement more easily. The experimental results demonstrate the feasibility of quadrature detection for self-mixing optical measurement. This Letter provides guidance for the design of self-mixing interferometers.

OCIS codes: (280.3420) Laser sensors; (140.5960) Semiconductor lasers; (230.0040) Detectors; (120.3180) Interferometry.

https://doi.org/10.1364/OL.43.002154

Optical feedback interference, also named self-mixing interference (SMI), underwent a rapid technical development with the advent of semiconductor lasers suitable for self-mixing. SMI optical measurement has been variously applied in displacement, vibrations, flow speed, absolute distance, and other laser-related measurements [1–13].

In SMI optical measurements for vibration, the differential vibrometer is obtained by electronic subtraction of signals from two vibrometer channels [14], which take the advantage that channels are servo stabilized and thus insensitive to speckle and other sources of amplitude fluctuation, but the focusing will be a problem when measuring vibrating objects of different distances with two optical heads. In this subtractive noise rejection scheme, if the optical system is adjusted perfectly so that the two photocurrents are exactly equal, the noise and the DC can be canceled, leaving only the signal. Because the adjustment required is a little complex, and because the intensity of the signal beam usually varies somewhat during a measurement, the currents cannot be exactly equal at all times. Also, a balanced detector for self-mixing interferometry was proposed [15], which is able to cancel the electromagnetic disturbances coupled with the laser pump current and the TIA. The balanced detection also removes any signal due to the LD modulations, including noise and disturbances on LD power supplies. In fact, the two signals acquired from the two facets of the beam splitter are not always kept the opposition phase, as it was found [16]. Randone and Donati had also noticed the phase concordance of the front output and the rear output (or, zero phase shift), and they have reconciled apparently contradictory results reported by several authors about the phase and the amplitude of the different outputs [17]. So this will limit the application of the balance detection proposed by Li *et al.*

A quadrature demodulation technique for the self-mixing interferometry displacement sensor was also proposed [18], and the quadrature beam is obtained by the phase modulation of an electro-optic modulator (EOM) in the external cavity. Mutual independent orthogonal polarized light is obtained by using AOM [19,20].

Some researchers had looked into using the beam splitter for interferometry to improve the accuracy of distance measurement, but not with the self-mixing interferometry approach, such as US patent US6,741,357 and the example in [21]. In this Letter, without using EOM or AOM, we propose a method that by just rotating the beam splitter by 22.5 deg to make the two self-mixing signals from the two facet quadratures, their angle information can be demodulated by the arctangent method, and then the displacement of the vibration objects can be extracted. What we emphasize here is that the "quadrature" we used here is for the temporal phase, not for the spatial location of the beam splitter.

The experimental setup is shown in Fig. 1. We applied the quadrature detection without the laser current modulation, in order to simplify the measurement systems. The laser source is a low-power single-mode visible Laser diode (model RLD65NZX2, by ROHM) with a built-in monitor PD, emitting up to 7 mW at $\lambda = 650$ nm on a single longitudinal mode. When we measure the vibration on the small speaker surface, it is driven by a 39-mA constant DC current. The optical section consists of an adjustable laser diode collimation tubes premounted with an aspheric lens. The position of this lens can be adjusted by up to 2.5 mm by rotating the cap on the end of the tube. The focus can be adjusted by threading the mounted lens in or out, and a beam splitter with reflection $R = 10\%$ is used. It is enough to have a good signal on the external PD without introducing a significant loss on the

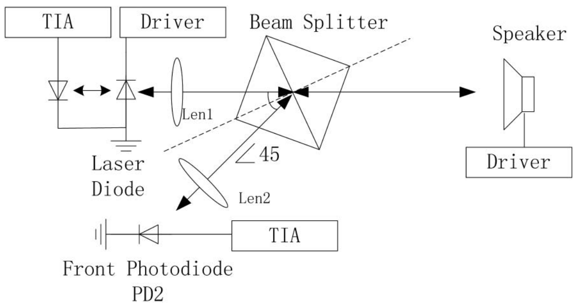

Fig. 1. Schematic of the experimental setup.

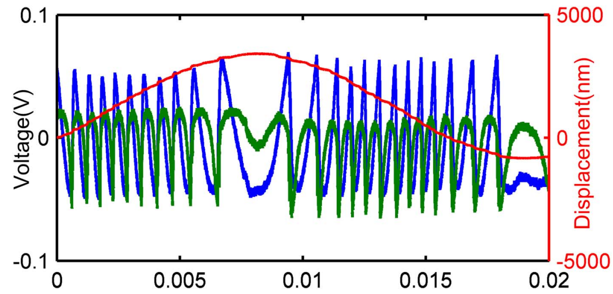

Fig. 2. SMI signals induced by a vibrating target. The upper trace is the calculated displacement, the middle trace is the monitor PD (PD1) output, and the lower trace is the front PD (PD2) output.

SMI measurement channel [15]. The front PD (PD2 in Fig. 1) is a build-in photodiode of another laser diode with same model (RLD65NZX2, by ROHM), and it is driven by a 22-mA current slightly above the threshold current in order to get the valid feedback photodiode signal, while the rear one (PD1 in Fig. 1) is the LD monitor PD. The first reason we use the same laser diode to detect the front signal is that the built-in monitor PD has the same optical detecting characteristic. The second reason is that we can use the same amplifier circuit, which has the ability of adjustable gain and adjustable offset (other PD also has been tested, and the result is the same). A second adjustable lens is also used for focusing the light on PD2. The angle between PD1 and PD2 is set to 45 deg by rotating the beam splitter by 22.5 deg. This is the novelty of this method. A good explanation of all the reflections and transmissions happening at the beam splitter and why the two signals are quadrature are still being investigated. The benefit from using the beam splitter with two detectors is that two the quadrature signals can easily be acquired.

The optical system is realized for having almost the same structure. A LT1169 amplifier is used to read the photocurrents. It is a suitable amplifier for photocurrent amplifier application. Two amplifiers (model LT1122) provide the offset and the gain adjustment. The self-mixing signals of the two detectors may change with the rotation of the beam splitter, and the two signals will be quadrature when the angle between the two detectors becomes 45 deg. Therefore, there is no need for a special method to demodulate the displacement of the vibrating object. The common arctangent method can be used to demodulate the signal. We can write the outputs from the front detector and the back detector as I1 and I2, respectively. As for the half wavelength corresponding to 2π, the displacement of the vibration can be written as

$$\text{displacement} = \text{unwrap}\left(\arctan\left(\frac{I_1}{I_2}\right)\right) \cdot \frac{\lambda}{2 \cdot 2\pi}, \quad \textbf{(1)}$$

where λ is the wavelength of the laser diode. Unwrap is the function for unwrapping the phase angle. This function corrects the radian phase angles by adding multiples of $\pm 2\pi$ when absolute jumps between consecutive phase angle are greater than or equal to the jump tolerance of the π radians. Arctan is the inverse tangent. The conventional method is complex to get to the phase, but this method simplifies the demodulation process just by taking the two detectors and rotating the beam splitter.

Figure 2 shows the signals acquired for a vibrating target with a 50-Hz vibration frequency. The SMI signals are caused by a vibrating small speaker. The displacement calculated by the proposed method is 4256 nm, which is in accordance with the estimated one by the fringe counting method. The fringe number is 13, so the peak of vibration is about 4225 nm.

Figure 3 shows the comparison between the SMI signal and the Hilbert transform signal. The Hilbert transform of the rear PD (PD1) output is in accordance with the monitor PD (PD2) output on the right part, and the Hilbert transform of the rear PD (PD1) output has opposite sign with monitor PD (PD2) output on the left part, so the phase is quadrature on both sides.

The detection results with different vibration frequencies are shown in Figs. 4 and 5. The 100-Hz and 200-Hz vibration results are shown in Fig. 4. They are lower frequency vibrations,

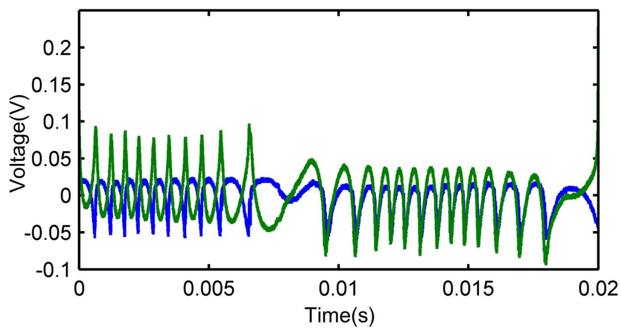

Fig. 3. Comparison between the SMI signal and the Hilbert transform signal. The lower signal is the monitor PD (PD2) output; the upper signal is the Hilbert transform of the rear PD (PD1) output.

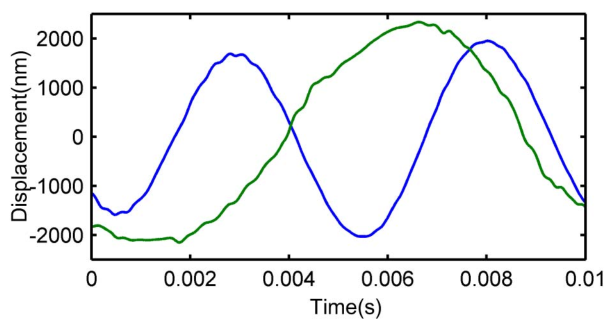

Fig. 4. Detection result with different vibration frequency. The upper trace is the measurement result of micro-displacement with a frequency of 100 Hz, and the lower trace is the measurement result of micro-displacement with a frequency of 200 Hz.

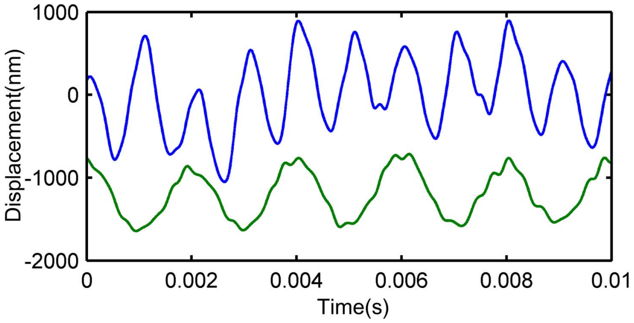

Fig. 5. Detection result with different vibration frequency. The upper trace is the measurement result of micro-displacement with a frequency of 1000 Hz, and the lower trace is the measurement result of micro-displacement with a frequency of 500 Hz.

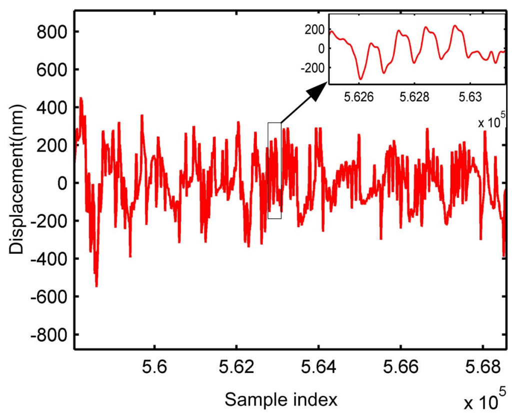

Fig. 6. Partial detection result with 1000-Hz vibration frequency under low speaker volume. Right upper trace is the zoomed figure of micro-displacement within the square.

and slightly higher frequencies of 500 Hz and 1000 Hz are shown in Fig. 5. From the upper trace in Fig. 5, we can see that the peak-to-peak value of displacement is about 1000 nm. It can calculate the displacement between the half wavelength, so the resolution of this method is just limited by the signal quality, and the resolution is better than half of the wavelength of the laser diode.

But if the amplitude of vibration is smaller than half of the wavelength, the signal will devastate. The partial detection result with a 1000-Hz vibration frequency under low speaker volume is shown in Fig. 6, and the whole sampling time is 10 s. The right upper trace is zoom figure of micro-displacement within the square, and the 1000-Hz vibration wave can be seen. The FFT analysis is undertaken, and the 1000-Hz vibration component can be clearly identified, as seen in Fig. 7. So, it is verified that the proposed quadrature demodulation method can extract displacement information from the quadrature self-mixing signals, which are obtained by just rotating the beam splitter with a certain angle.

In conclusion, we proposed a quadrature-detecting method for self-mixing interferometry, which is able to calculate the displacement of the vibrating objects from the two quadrature signals. The quadrature detection also cancels any reference

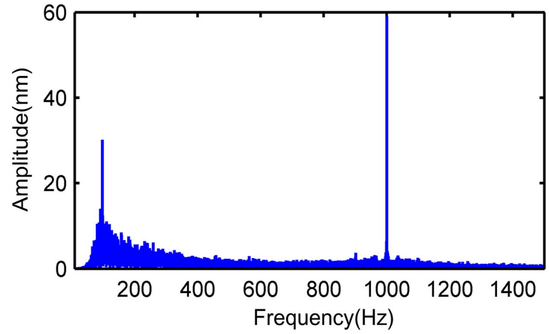

Fig. 7. FFT analysis result of micro-displacement with frequency of 1000 Hz.

signal like normal IQ demodulation. In addition, it simplifies the calculation process of SMI signal demodulation. The slight loss induced by the beam splitter is negligible with respect to the obtained calculation convenience. This technique can be applied to several SMI measurements, and it is especially useful in the case of SMI signal demodulation.

Funding. Development Program of Jilin Province (20160203014GX, 2015Y028); Fund of State Key Laboratory of Applied Optics of Changchun Institute of Optics, Fine Mechanics and Physics; Youth Innovation Promotion Association of the Chinese Academy of Sciences; National High Technology Research and Development Plan (2015AA042603).

REFERENCES

1. V. Contreras, J. Toivonen, and H. Martinez, Opt. Lett. **42**, 2221 (2017).
2. G. Giuliani, M. Norgia, S. Donati, and T. Bosch, J. Opt. A **4**, S283 (2002).
3. S. Donati, Laser Photon. Rev. **6**, 393 (2012).
4. A. Magnani, A. Pesatori, and M. Norgia, IEEE Trans. Instrum. Meas. **63**, 1804 (2014).
5. K. Otsuka, Opt. Lett. **39**, 1069 (2014).
6. L. Scalise, Y. Yu, G. Giuliani, and T. Bosh, IEEE Trans. Instrum. Meas. **53**, 223 (2004).
7. D. Melchionni, A. Magnani, A. Pesatori, and M. Norgia, Appl. Opt. **54**, 9637 (2015).
8. M. Norgia, A. Pesatori, and S. Donati, IEEE Trans. Instrum. Meas. **65**, 1478 (2016).
9. M. Norgia, A. Magnani, and A. Pesatori, Rev. Sci. Instrum. **83**, 045113 (2012).
10. M. Norgia, A. Pesatori, and C. Svelto, IEEE Trans. Instrum. Meas. **56**, 1373 (2007).
11. Y. Yu, G. Giuliani, and S. Donati, IEEE Photon. Technol. Lett. **16**, 990 (2004).
12. P. Dean, J. Keeley, A. Valavanis, K. Bertling, Y. Lim, T. Taimre, R. Alhathlool, L. Li, D. Indjin, A. Rakić, E. Linfield, and A. Davies, Opt. Lett. **40**, 950 (2015).
13. L. Persson, F. Andersson, M. Andersson, and S. Svanberg, Appl. Phys. **B87**, 523 (2007).
14. S. Donati, M. Norgia, and G. Giuliani, Appl. Opt. **45**, 7264 (2006).
15. K. Li, F. Cavedo, A. Pesatori, C. Zhao, and M. Norgia, Opt. Lett. **42**, 283 (2017).
16. W. Wang, W. J. O. Boyle, K. T. W. Grattan, and A. W. Palmer, J. Lightwave Technol. **12**, 1577 (1992).
17. E. M. Randone and S. Donati, Opt. Express **14**, 9788 (2006).
18. D. Guo, Opt. Commun. **284**, 5766 (2011).
19. S. Zhang, S. Zhang, Y. Tan, and L. Sun, Opt. Lett. **41**, 844 (2016).
20. S. Zhang, S. Zhang, Y. Tan, and L. Sun, Opt. Lett. **41**, 4827 (2016).
21. P. Gregorčič, T. Požar, and J. Možina, Opt. Express **17**, 16322 (2009).