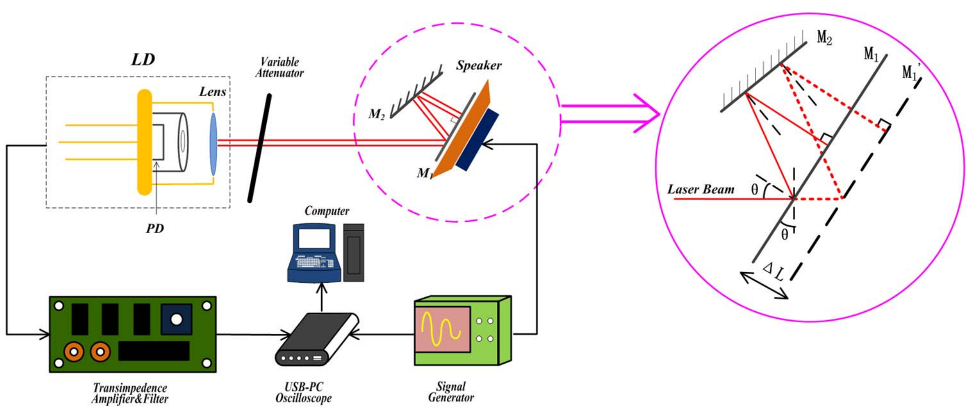
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Obtaining High Fringe Precision in Self-Mixing Interference Using a Simple External Reflecting Mirror

Volume 5, Number 3, June 2013

Lu Wang
Xun Luo
Xiulin Wang
Wencai Huang



DOI: 10.1109/JPHOT.2013.2264277
1943-0655/$31.00 ©2013 IEEE

Obtaining High Fringe Precision in Self-Mixing Interference Using a Simple External Reflecting Mirror

Lu Wang,[1] **Xun Luo,**[1] **Xiulin Wang,**[2] **and Wencai Huang**[1]

[1]Department of Electronic Engineering, Xiamen University, Xiamen 361005, China
[2]Department of Physics, Jimei University, Xiamen 361021, China

DOI: 10.1109/JPHOT.2013.2264277

Manuscript received April 9, 2013; revised May 9, 2013; accepted May 13, 2013. Date of publication May 20, 2013; date of current version May 30, 2013. This work was supported by the National Natural Science Foundation of China under Grant 61108019. Corresponding author: W. Huang (e-mail: huangwc@xmu.edu.cn).

Abstract: Based on the study of laser diode self-mixing interference effects, a simple and effective method that can improve fringe precision is presented. By employing an external reflecting mirror, theoretical and experimental results show an assured increase about two or three times in the resolution of the displacement measurement, which means a fringe shift is corresponding to a near 1/6 wavelength displacement of the target. At a small angle range, when the fringe precision is not fixed, this method can still have a relative high precision and a large measurement range. The maximum measurable displacement and error of precision are also discussed.

Index Terms: Self-mixing interference (SMI), fringe precision.

1. Introduction

Since the self-mixing interference (SMI) effect was reported 50 years ago, the well-known and viable technique has attracted considerable attention. In the self-mixing interferometric configuration, when the light reflected or backscattered by the external target re-enters the laser cavity, where it mixes with the lasing electromagnetic field, the frequency and power of the emitting light will be modulated. Compared with the traditional interference such as the Michelson interference, the advantages of SMI are its low cost and compactness, just needing a laser and a photodiode (PD). The optic path is very simple and self-aligning such that the reference path is not required. In recent decades, this SMI effect based on solid-state laser [1], vertical cavity surface emitting laser (VCSEL) [2], distributed feedback laser (DFB) [3], and fiber laser [4] has been widely studied. The SMI signals can carry the information of the target; therefore, this technique has been used for a wide variety of measurements, including velocity [5], absolute distance [6], displacement [7], vibration [8], and thickness [9].

In the typical SMI system, it is a restriction that a fringe shift of SMI signal corresponds to only a half wavelength displacement in the fringe-counting method. Cheng and Zhang [10] reported that they provided a method to discriminate the direction and improves the resolution 17 times. However, their system requires a partially reflecting measured target whose transmittance and reflectance are difficult to know in actual measurements; hence, this method is inconvenient to be applied since the fringe precision is unpredictable. In this paper, we present a simple method that can effectively improve the fringe precision merely by employing an external reflecting mirror. Fringe

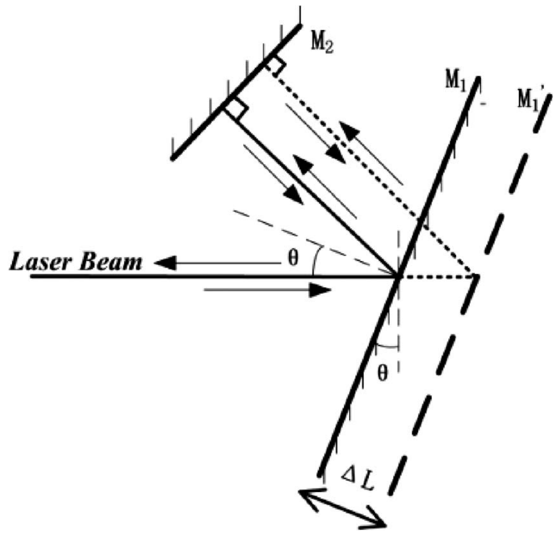


Fig. 1. Schematic of the optical path.

precision values of near 1/4 and 1/6 wavelengths, respectively, were obtained by simply adjusting the external reflect mirror to increase the reflection number of the target. The experimental results have a good correspondence with theoretical analysis. The practical limitations related to obtain a higher fringe precision are analyzed theoretically.

2. Theoretical Analysis

The theory of SMI effects has been widely studied [11], [12]. In the presence of optical feedback, the laser cavity and the external cavity form a three-facet Fabry–Pérot optical system. Based on an analytical steady-state solution, the emitted laser power usually is written as

$$P(\phi) = P_0[1 + mF(\phi)] \tag{1}$$

which is amplitude modulated by a periodic (period $T = 2\pi$) interferometric function $F(\phi)$. In (1), P_0 is the laser power without optical feedback and m is the modulation index; $\phi = 2kL = 4\pi L/\lambda$ is the optical phase shift of the external path with k being the wave vector, λ being the wavelength, and L being the variation of distance from the laser diode (LD) to the target. The shape of the function $F(\phi)$ depends on feedback strength parameter C [13], which, in turn, depends on laser parameters, mismatch coefficient, target distance, and laser cavity length. Since parameter C is unrelated to our purpose, we would stay only in the weak self-mixing regime $(C < 1)$ in the experiment. For the periodic interferometric function, if the minimum displacement of the target that can cause a fringe shift (corresponding to a 2π external phase shift) is set to ΔL, the relationship between the changed phase $(\Delta\phi)$ and the small displacement of the target (ΔL) can be given as

$$\Delta\phi = 2\pi = 4\pi\frac{\Delta L}{\lambda}. \tag{2}$$

Therefore, from (2), $\Delta L = \lambda/2$, that is, the fringe precision in a typical SMI system (reflected vertically), is half wavelength of the displacement.

In our design (see Fig. 1), which is different from the case of being reflected vertically, the vibratory target (M_1) is first rotated at a certain angle (θ). Then an external reflecting mirror (M_2) is employed to make the light re-enter the laser cavity along backtrack. Therefore, the laser beam will be reflected twice by the target. In the schematic, ray propagation analysis shows that the actual optical path is $\Delta L' = 2\Delta L\cos\theta$, and it is no longer a real displacement of the target (see "ΔL" in

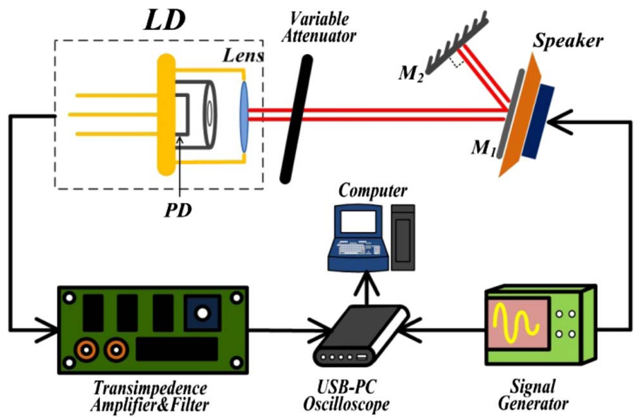


Fig. 2. Experimental setup to improve fringe precision in SMI.

Fig. 1). The changed phase $(\Delta\phi)$, which can cause a fringe shift in (2), should be fixed by the actual optical path $(\Delta L')$, and the variation of the external phase can be written as

$$\Delta\phi = 2\pi = 4\pi\frac{2\Delta L\cos\theta}{\lambda}. \tag{3}$$

Therefore, from (3), the actual resolution can be expressed as

$$\Delta L = \frac{\lambda}{4\cos\theta} \tag{4}$$

and depends on angle θ. In other words, the number of SMI signal fringes will become $2\cos\theta$ times in the same amplitude of target.

3. Experiment and Results

The experiment setup is shown in Fig. 2. We use an LD (FU650AD5_C9N) as the light source, emitting up to 5 mW at 650 nm on a single longitudinal mode, driven by a constant current supply. A piece of M_1 is pasted on the speaker (driven by AFG3022 signal generator and vibrates harmonically), which is mounted on a microrotating stage placed at a distance of 12 cm from the laser source. M_2 is 2 cm away from the speaker to keep the laser intensity and working space. The angle of M_2 is adjusted to ensure that the collimated beam re-enters the laser cavity. The changes of laser power are detected by a power-monitor PD packaged in the LD and transformed into current, which will be amplified by a transimpedance amplifier and acquired by a computer via a PC-USB oscilloscope (Hantek-DSO3604A).

At first, the external mirror (M_2) is removed, and adjusting the angle of the speaker makes the laser beam reflected vertically. Fig. 3(a) and (b) illustrates the waveform of the 3.6-V speaker driving voltage and the corresponding waveform of the SMI, respectively. Obviously, the number of fringes will decrease with the reduction of the driving voltage. When the driving voltage is reduced to 1 V [see Fig. 3(c)], it is hard to observe a fringe in the SMI signal, as shown in Fig. 3(d). It indicates that the vibratory displacement is less than 1/2 wavelength when the driving voltage is 1 V. Fig. 3(e) shows the SMI signal by rotating the speaker with a small angle and adjusting M_2 to make the laser beam re-enter the laser cavity along backtrack. In this case, one more fringe appears in the SMI signal. The result demonstrates clearly that the fringe precision is improved by employing an external reflecting mirror.

As shown in the above theoretical analysis, the improvement of fringe precision depends on the rotated angle of the target (4). Therefore, the SMI signals at different angles are recorded, as shown in Fig. 4. For each angle, we fine-tune M_2 and the variable attenuator to achieve the best SMI signal. Fig. 4 clearly shows that the number of fringes gradually decreases with the increase in the

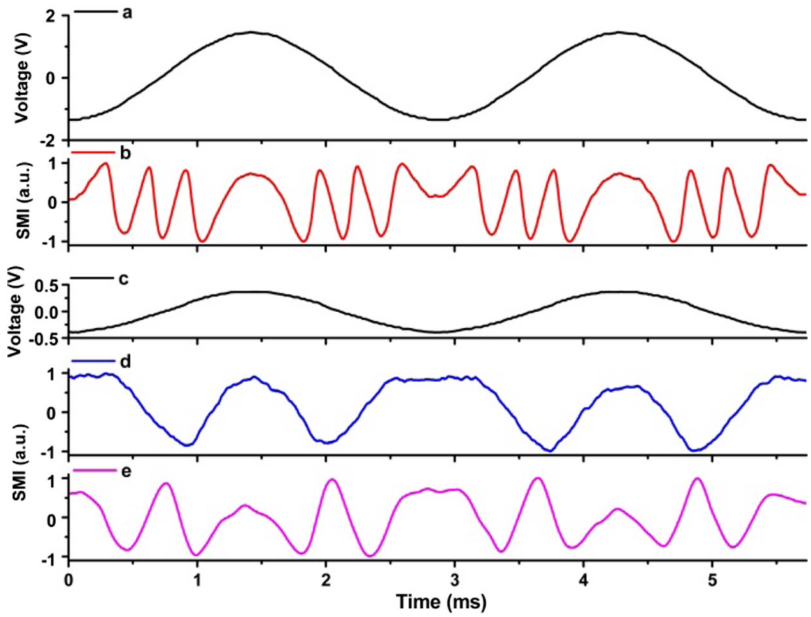


Fig. 3. (a) 3.6 V driving voltage. (b) SMI signal under 3.6 V without M_2. (c) 1.0 V driving voltage. (d) SMI signal under 1.0 V without M_2. (e) SMI signal under 1.0 V with M_2.

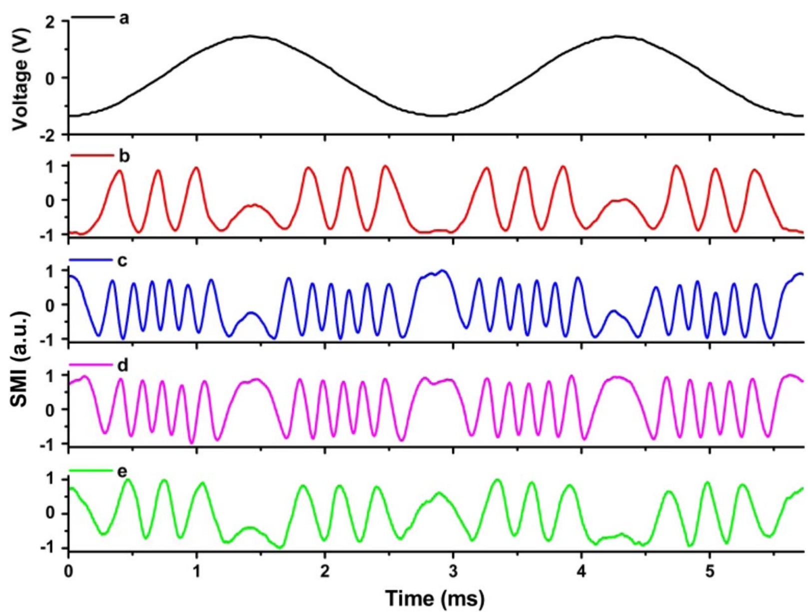


Fig. 4. Experimental results of SMI signals at different angles. (a) Driving voltage. (b) $\theta = 0^\circ$ without M_2. (c) $\theta = 10^\circ$ with M_2. (d) $\theta = 30^\circ$ with M_2. (e) $\theta = 60^\circ$ with M_2.

rotated angle under the same driving voltage of the speaker. When the rotated angle is 60°, the SMI signal is renewed to the initial waveform without M_2 [see Fig. 4(b)]. Therefore, higher fringe precision could be obtained with a smaller angle of the speaker. When $\theta = 10^\circ$, the fringe precision is $\lambda/3.94$, which is close to the ideal precision $\lambda/4$.

The above study shows that increasing the optical path can effectively improve the precision. Therefore, as shown in Fig. 5, we change the experimental optical path to increase the number of

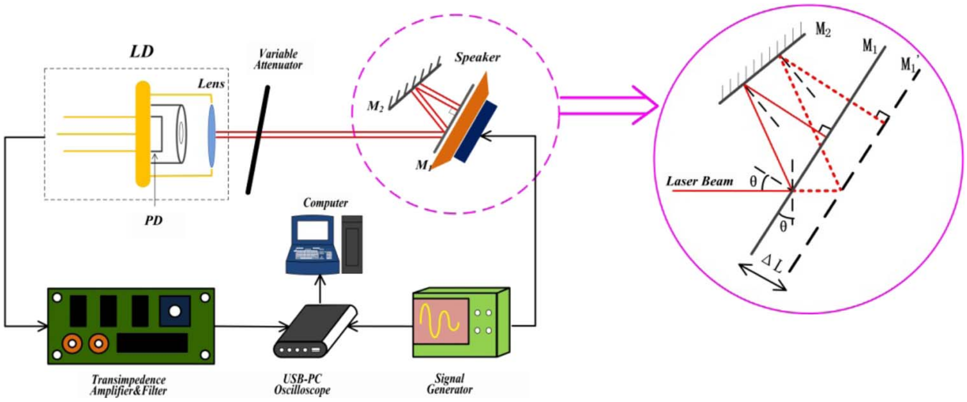


Fig. 5. Schematic of improving fringe precision with three reflections.

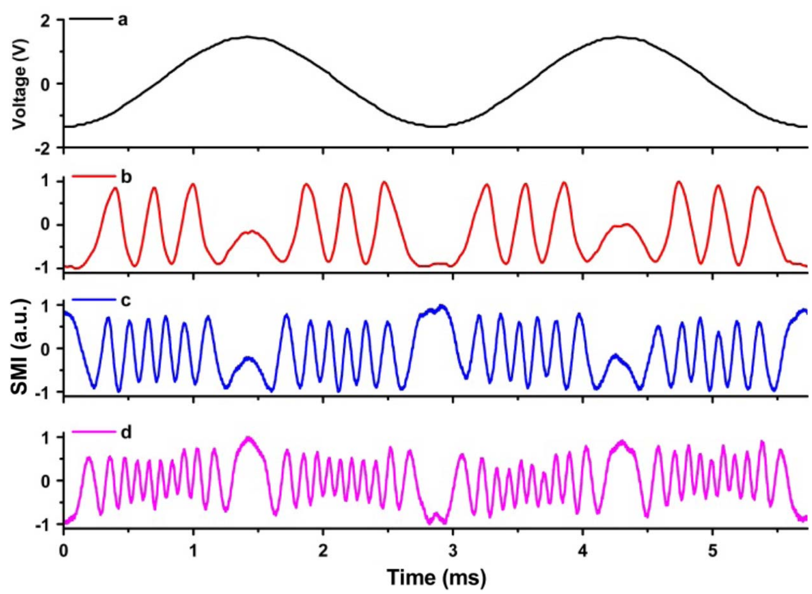


Fig. 6. Experimental results of SMI signals. (a) Driving voltage. (b) Reflected vertically without M_2. (c) Reflected twice with M_2. (d) Reflected thrice with M_2.

reflections and the laser beam can be reflected thrice by the target. Being similar to Fig. 1, fixing (2) with the actual optical path $(\Delta L = (2\cos\theta + 1)\Delta L)$ in Fig. 5, we get

$$\Delta\phi = 2\pi = 4\pi \frac{(2\cos\theta + 1)\Delta L}{\lambda} \tag{5}$$

which means that the resolution will become $\Delta L = \lambda/(4\cos\theta + 2)$.

In this experiment, we set the rotated angle at about $\theta = 10^\circ$. Compared with the cases of being reflected vertically and reflected twice, the SMI signals are recorded in Fig. 6. Obviously, the number of fringes is increased from three and six to ten. The experimental results are in good consistence with the theoretical analysis. Under this circumstance, the fringe precision can be raised to 1/6 wavelength.

4. Discussion

In principle, as long as the reflected light is incident normally on the mirror (M_1 or M_2) at any time, this method should be possible to have an arbitrarily high number of passes between M_1 and M_2,

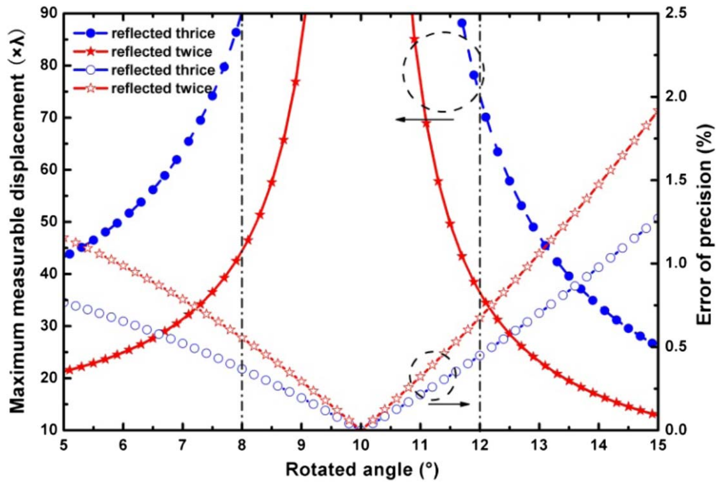


Fig. 7. Maximum measurable displacement and error of precision.

resulting in an arbitrary displacement sensitivity gain (G)

$$G = \frac{1}{\cos\theta} + \sum_{n=1}^{N-1} \frac{\cos\frac{N\theta}{N-1}}{\cos\frac{(n-1)\theta}{N-1}\cos\frac{n\theta}{N-1}} \tag{6}$$

where θ is the rotated angle and N is the number of reflections $(N \geq 2)$ on M_1. In other words, the resolution is $P_{N,\theta} = \Delta L = \lambda/[2G(N,\theta)]$. From (6), it can be seen that a higher fringe precision relies on a smaller angle and a larger number of reflections. However, with the increase in the number of reflections, the final incidence angle θ_{N-1} $(\theta_{N-1} = \theta/(N-1))$ is so small that adjusting the external mirror will be difficult. Besides, there are two other factors that must be considered in the actual experiment: a) Due to multiple reflections between M_1 and M_2, the laser beam collimation must be taken into account to ensure that the light intensity is high enough; and b) the length of M_1 and the minimum distance between M_1 and M_2. Obviously, the number of reflections depends on the length of the target. When the target's area is small, it is difficult to guarantee multiple reflections on the target. Similarly, for a fixed number of reflections, a longer distance will require a longer length of the target. These three factors are mutual restrictions, so in practice, for different lengths of the target, it is not easy to adjust the external mirror to maintain multiple reflections well.

As a final remark, we discuss the application of this method in actual measurement. Reflecting the laser beam twice or thrice can be easily achieved, and the rotated angle in the measurement process is needed to fix the fringe precision though function $1/\cos\theta$ increases slowly within a certain range of angle (0°–15°) and is close to 1. If the precision is regarded as 1/4 or 1/6 wavelength, it is no doubt that the error will raise gradually with the increase in the displacement. Therefore, when the rotated angle value is ignored, to reduce the error, we can set $\lambda/3.94$ or $\lambda/5.94$ (reflected twice or reflected thrice, $\theta = 10^\circ$) as a moderate and standard precision into the calculation of displacement, instead of using the actual but unknown precision. In the fringe-counting method, the peak-to-peak displacement is calculated as $N_F P_{N,\theta}$, where N_F is the fringe number in half period and the error is within $P_{N,\theta}$. However, due to the uncertainty of the angle, every fringe can cause an error of calculation $(\Delta P = |P_{N,10^\circ} - P_{N,\theta}|)$. It will reach the maximum measurable displacement until $N_F \Delta P$ compensates the D-value of different precision values. The error of precision (E_p) can be expressed as $E_p = \Delta P/P_{N,\theta}$. Fig. 7 shows the maximum measurable displacement, which means that the error is lower than that of the typical situation (reflected vertically without using M_2) and the error of precision at small angles caused by the uncertainty of the incident angle. For our purpose, an approximate angle $(\theta = 10^\circ)$ is expected to obtain a relative high displacement sensitivity gain and good operability.

As can be seen from Fig. 7, the closer the rotated angle is to 10°, the larger the measurable displacement will be and the smaller the error will be. When the uncertainty of the angle is kept within $\pm 2°$, the maximum measurable displacements increase rapidly and are far larger than 36λ (reflected twice) and 74λ (reflected thrice), respectively. Meanwhile, the errors of precision are less than 0.67% (reflected twice) and 0.45% (reflected thrice). Therefore, when the rotated angle is relatively small, it is not necessary to measure the exact value of the angle in practical applications, as long as the measured results are less than these ranges, and this method without the rotated angle can still have a relative high precision and a large measurement range. It must be emphasized again that this method will not have any limit if the rotated angle is measured.

5. Conclusion

A simple and effective method that can obtain a high fringe precision in SMI by employing an external reflecting mirror has been proposed. Theoretical analysis shows that the resolution of measurement could be enhanced many times compared with the traditional SMI sensor, and meanwhile, the fringe precision can reach to near 1/6 wavelength displacement of the target in the experiment. The compact structure can be adjusted readily in practical applications according to different requirements, and it could be of great use in the measurement of microvibration.

References

[1] K. Otsuka, R. Kawai, Y. Asakawa, and T. Fukazawa, "Highly sensitive self-mixing measurement of Brillouin scattering with a laser-diode-pumped microchip LiNdP4O12 laser," *Opt. Lett.*, vol. 24, no. 24, pp. 1862–1864, Dec. 1999.

[2] J. R. Tucker, A. D. Rakic, C. J. O'Brien, and A. V. Zvyagin, "Effect of multiple transverse modes in self-mixing sensors based on vertical-cavity surface-emitting lasers," *Appl. Opt.*, vol. 46, no. 4, pp. 611–619, Feb. 2007.

[3] D. Han, M. Wang, and J. Zhou, "Self-mixing speckle interference in DFB lasers," *Opt. Exp.*, vol. 14, no. 8, pp. 3312–3317, Apr. 2006.

[4] L. Lu, J. Y. Yang, L. H. Zhai, R. Wang, Z. G. Cao, and B. L. Yu, "Self-mixing interference measurement system of a fiber ring laser with ultra-narrow linewidth," *Opt. Exp.*, vol. 20, no. 8, pp. 8598–8607, Apr. 2012.

[5] S. Shinohara, A. Mochizuki, H. Yoshida, and M. Sumi, "Laser Doppler-velocimeter using the self-mixing effect of a semiconductor-laser diode," *Appl. Opt.*, vol. 25, no. 9, pp. 1417–1419, May 1986.

[6] F. Gouaux, N. Servagent, and T. Bosch, "Absolute distance measurement with an optical feedback interferometer," *Appl. Opt.*, vol. 37, no. 28, pp. 6684–6689, Oct. 1998.

[7] C. Bes, G. Plantier, and T. Bosch, "Displacement measurements using a self-mixing laser diode under moderate feedback," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 4, pp. 1101–1105, Aug. 2006.

[8] K. Otsuka, K. Abe, J.-Y. Ko, and T.-S. Lim, "Real-time nanometer-vibration measurement with a self-mixing microchip solid-state laser," *Opt. Lett.*, vol. 27, no. 15, pp. 1339–1341, Aug. 2002.

[9] M. T. Fathi and S. Donati, "Thickness measurement of transparent plates by a self-mixing interferometer," *Opt. Lett.*, vol. 35, no. 11, pp. 1844–1846, Jun. 2010.

[10] X. Cheng and S. Zhang, "Intensity modulation of VCSELs under feedback with two reflectors and self-mixing interferometer," *Opt. Commun.*, vol. 272, no. 2, pp. 420–424, Apr. 2007.

[11] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electron.*, vol. QE-16, no. 3, pp. 347–355, Mar. 1980.

[12] W. M. Wang, K. T. V. Grattan, A. W. Palmer, and W. J. O. Boyle, "Self-mixing interference inside a single mode diode laser for optical sensing applications," *J. Lightwave Technol.*, vol. 12, no. 9, pp. 1577–1587, Sep. 1994.

[13] G. Giuliani, M. Norgia, S. Donati, and T. Bosch, "Laser diode self-mixing technique for sensing applications," *J. Opt. A, Pure Appl. Opt.*, vol. 4, no. 6, pp. S283–S294, Nov. 2002.