Profile measurement using a self-mixing laser diode

Han Wang
University of Wollongong, hw894@uowmail.edu.au

Yuxi Ruan
University of Wollongong, yr776@uowmail.edu.au

Lingzhi Cao
Zhengzhou University of Light Industry

Yanguang Yu
University of Wollongong, yanguang@uow.edu.au

Jiangtao Xi
University of Wollongong, jiangtao@uow.edu.au

See next page for additional authors

Profile measurement using a self-mixing laser diode

Abstract

When a fraction of external optical feedback re-enters inside cavity of a laser diode (LD), the laser intensity and its wavelength will thus be altered. The LD in this case is often called as a self-mixing laser diode (SMLD). This paper presents an SMLD for profile measurement. The LD is modulated by the injection current in triangular waveform and a target to be measured is installed on a mechanic scanning device. The reflection light by the target contains its surface profile. The profile information is then carried in the laser intensity and can be pickup by a photodiode packaged in the rear of the LD. We call this modulated laser intensity as self-mixing interferometric (SMI) signal. In this paper, a new algorithm is developed to retrieve the profile from the SMI signal. Results show that the proposed design is able to achieve the measurement of profile with high resolution.

Disciplines

Engineering | Science and Technology Studies

Publication Details

H. Wang, Y. Ruan, L. Cao, Y. Yu, J. Xi, Q. Guo, J. Tong & J. Zhang, "Profile measurement using a self-mixing laser diode," in Semiconductor Lasers and Applications VIII, 2018, pp. 1081211-1-1081211-8.

Authors

Han Wang, Yuxi Ruan, Lingzhi Cao, Yanguang Yu, Jiangtao Xi, Qinghua Guo, Jun Tong, and Jitao Zhang

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Profile measurement using a self-mixing laser diode

Han Wang, Yuxi Ruan, Lingzhi Cao, Yanguang Yu, Jiangtao Xi, et al.

Han Wang, Yuxi Ruan, Lingzhi Cao, Yanguang Yu, Jiangtao Xi, Qinghua Guo, Jun Tong, Jitao Zhang, "Profile measurement using a self-mixing laser diode," Proc. SPIE 10812, Semiconductor Lasers and Applications VIII, 1081211 (6 November 2018); doi: 10.1117/12.2500739

SPIE.

Event: SPIE/COS Photonics Asia, 2018, Beijing, China

Profile measurement using a self-mixing laser diode

Han Wang[a], Yuxi Ruan[a], Lingzhi Cao*[b], Yanguang Yu[a], Jiangtao Xi[a], Qinghua Guo[a], Jun Tong[a] and Jitao Zhang[b]

[a]School of Electrical, Computer and Telecommunication Engineering, University of Wollongong, Northfields Avenue, Wollongong, NSW, Australia, 2522; [b]School of Electrical and Information Engineering, Zhengzhou University of Light Industry, Zhengzhou, Henan, China, 450000

ABSTRACT

When a fraction of external optical feedback re-enters inside cavity of a laser diode (LD), the laser intensity and its wavelength will thus be altered. The LD in this case is often called as a self-mixing laser diode (SMLD). This paper presents an SMLD for profile measurement. The LD is modulated by the injection current in triangular waveform and a target to be measured is installed on a mechanic scanning device. The reflection light by the target contains its surface profile. The profile information is then carried in the laser intensity and can be pickup by a photodiode packaged in the rear of the LD. We call this modulated laser intensity as self-mixing interferometric (SMI) signal. In this paper, a new algorithm is developed to retrieve the profile from the SMI signal. Results show that the proposed design is able to achieve the measurement of profile with high resolution.

Keywords: laser diode, self-mixing interferometry, profile measurement

1. INTRODUCTION

The profile measurement of an object is needed for many applications such as quality control in a production line, biomedicine, robotics, measurement of mechanical wear, and the recording of surface shape data. There are several known methods used for profile measurement: triangulation, fringe projection (so called Moire), interferometric methods, speckle interferometry and so on [1].

Self-mixing interferometry is new promising interferometric technology. It uses the self-mixing effect in laser, which occurs when a fraction of optical feedback provided by the external cavity (or target) re-enters inside cavity of a laser diode (LD). In this case, the laser intensity and optical frequency will then be altered. Such a laser diode is often called as a self-mixing laser diode (SMLD). The modulated laser intensity is called a self-mixing interferometric (SMI) signal. This is a minimal part-count scheme easy for engineering implementation with fast response and high sensitivity [2-6], which can be used for external cavity related such as displacement/distance, velocity, surface roughness [7,8], also for the LD associated parameters e.g. linewidth enhancement factor [9,10].

When such an SMLD is modulated by an injection current in periodic triangular waveform, the initial phase of the detected SMI signal in each triangular period contains the information related to the surface topology of the target fixed on the 2-D platform. To achieve high resolution and great accuracy, it requires to develop an advanced algorithm to retrieve the initial phase. As shown in figure 1, for realizing the measurement, a target with complex surface is fixed on a 2-D platform, we can use the controller to drive the platform to create a movement. By illuminating laser onto the target, the modulated LD power is referred as a SMI signal which can be detected by the photodiode (PD) packaged in the rear of the LD, amplified by a trans-impedance amplifier, and then recorded by an oscilloscope. In this case, the modulating period can be used to divide the surface of the target into pixels. By measuring the distance of each pixel, we can retrieve the target surface. The measuring resolution depends on the modulation frequency of the injection current.

In this paper, we propose to use the SMI technology for profile measurement and present a new method to increase the measurement resolution when the triangular modulation frequency is limited. Firstly, the related theory is presented for describing the laser phase obtained at the PD. Then the reconstruction algorithm is proposed, and the relevant simulation for re-establishing the profile of the target is implemented to verify the proposed method.

Semiconductor Lasers and Applications VIII, edited by Ning Hua Zhu, Werner H. Hofmann, Proc. of SPIE
Vol. 10812, 1081211 · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2500739

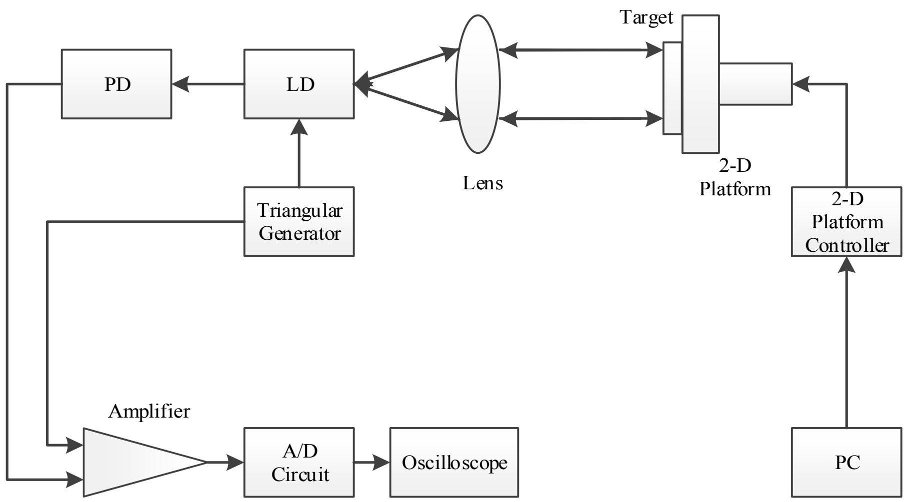

Figure 1. Schematic diagram of the experimental SMI system.

2. THEORETICAL MODELLING

With a triangular injection current and optical feedback, we can receive a step-shaped signal from the photodiode [11,12], which is expressed as (1):

$$I(t) = A(t) + B\cos\Phi(t) \tag{1}$$

$A(t)$ is the modulated intensity corresponding to a triangular modulated injection current. After removing the modulated signal intensity $A(t)$, a fringe-shaped SMI signal can be obtained. The intensity of the fringe-shaped SMI signal is defined as $B\cos\Phi(t)$, where B stands for the undulation coefficient determined by the target. A typical figure of step-shaped signal $I(t)$ and fringe-shaped signal $B\cos\Phi(t)$ are shown in figure 2.

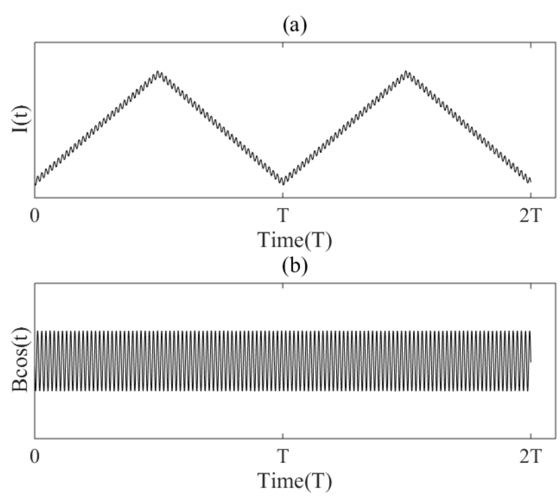

Figure 2. (a) step-shaped signal $I(t) = A(t) + B\cos\Phi(t)$; (b) fringe-shaped SMI signal $B\cos\Phi(t)$.

We express the external cavity length as $L_0 + d(t)$, where L_0 denotes the initial cavity length and $d(t)$ denotes the variation of the cavity length. The phase of SMI signal depends on the optical frequency $\upsilon_0 + \gamma t$ and the external cavity length $L_0 + d(t)$, which is expressed as below:

$$\Phi(t) = 4\pi \frac{\upsilon_0 + \gamma t}{c}(L_0 + d(t)) = 4\pi \frac{\upsilon_0}{c} L_0 + 4\pi \frac{\upsilon_0}{c} d(t) + 4\pi \frac{\gamma t}{c} L_0 + 4\pi \frac{\gamma t}{c} d(t) \quad (2)$$

The parameters used in the equations are defined as below in Table 1.

Table 1. Meaning of parameters in equations.

Parameters	**Meaning**
$I(t)$	Signal intensity with modulation and optical feedback
$A(t)$	Signal intensity related to modulation
$II_{FIX-T}(t)$, $II_T(t)$	Output intensity after removing the modulated signal for different targets
B, B_1, B_2	Undulation coefficient determined by target
$\Phi(t)$	Phase of SMI signal with a moving target
υ_0	Optical frequency without optical feedback
γ	Modulating efficient corresponding to optical frequency change
L_0	Initial external cavity length
$d(t)$	Displacement of target
ϕ_0	Constant initial phase of the SMI signal
$\phi(t)$	Phase relative to the displacement
f_C	Carrier frequency caused by optical feedback

The $4\pi \frac{\upsilon_0}{c} d(t)$ in the right part of (2) is the phase corresponding to the displacement generated by the target, which is denoted as $\phi(t)$. By applying FFT method to analyze the SMI signal and selecting the peak of the Fourier spectrum, we can find the carrier frequency f_C and then obtain the phase θ of fringe signal. The $\phi(t)$ can be calculated as $\phi(t) = \theta - \phi_0$, where ϕ_0 denotes the constant initial phase of the SMI signal. Thus, we can calculate the displacement from $\phi(t)$, as $d(t) = \lambda\phi(t)/4\pi$. λ is the wave length of the laser. This method is suitable for micro-displacement shorter than half wavelength.

2.1 Principle for phase measurement with Euler's formula expansion

We can define the output intensity with a fixed target after removing the modulated triangular signal as:

$$II_{FIX-T}(t) = B_1 \cos(2\pi f_C t + \phi_0) \quad (3)$$

And the intensity with a moving target after removing the modulated triangular signal is:

$$II_T(t) = B_2 \cos(2\pi f_C t + \phi_0 + \phi(t)) \quad (4)$$

According to Euler's formula expansion, for sampling points N, after applying FFT to $II_{FIX-T}(t)$, we can obtain $FFT(II_{FIX-T}(t))$, pick the $1 \sim N/2$ points as $FFT(\frac{B_1}{2}(e^{j(2\pi f_C t+\phi_0)}))$, denoted as $II_{FIX-T}(f)$. Similarly we can achieve $II_T(f)$, then

$$\frac{B_2 B_1}{4} e^{j\phi(t)} = IFFT(II_T(f)) \times [IFFT(II_{FIX-T}(f))]^*, \quad (5)$$

where * stands for the conjugate calculation. The phase $\phi(t)$ corresponding to the displacement can be calculated from (5), which leads to retrieve a displacement with high resolution and great accuracy. The flow chart of phase measurement is shown as below in figure 3.

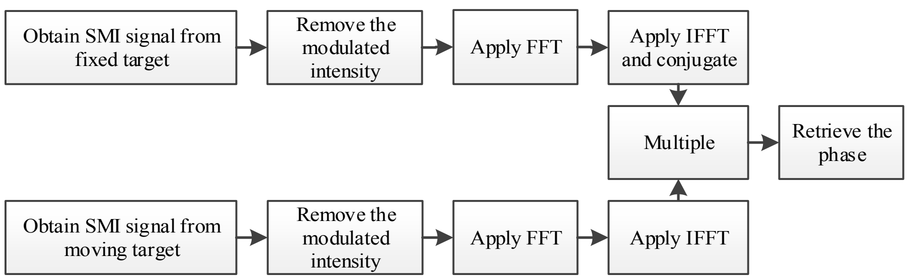

Figure 3. The flow chart for phase measurement.

2.2 Strategy of scanning

When scanning over a target with complex surface, the SMI signal received by PD contains the information of the profile. This scanning process can be regard as a displacement. By retrieving this displacement, we can re-establish the profile of the target.

According to the manual of the 2-D platform, the process of scanning can be set as a square waveform, as shown in figure 4. The distance between each scanning line is $1\mu m$.

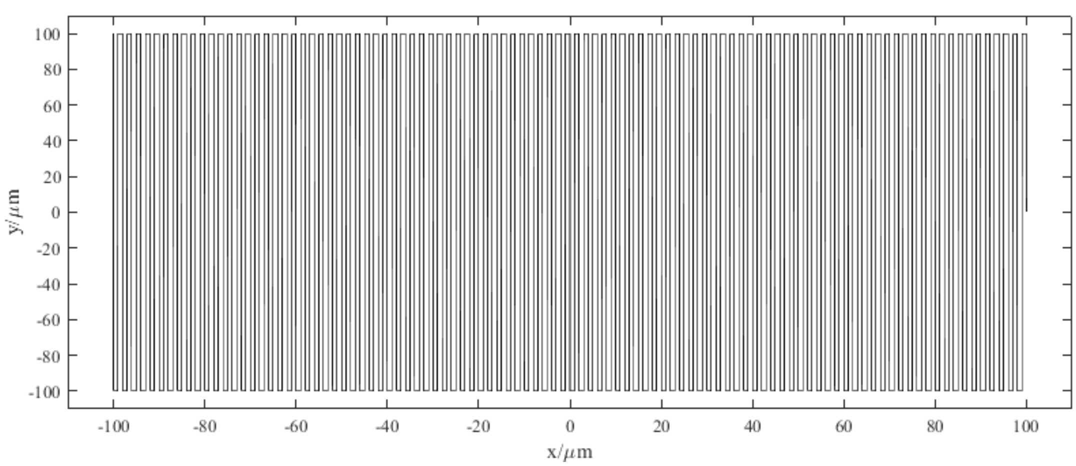

Figure 4. The set scanning process.

3. SIMULATION OF PROFILE RETRIEVING

3.1 Simulation results for the spherical surface

If the measured object is a spherical surface with a radius R , the profile can be expressed as,

$$z(x,y) = -(x^2 + y^2)/2R + 0.05 \quad (6)$$

where $x, y \in (-100\mu m, 100\mu m)$, and $R = 100mm$, all minus z values are set as 0. The profile of the spherical surface is shown as figure 5. For the proposed new algorithm, the output intensity of SMI signal with and without external cavity is expressed as (4) and (5), setting $B_1 = 3.5/60$, $B_2 = 7/60$, $\lambda = 780nm$, together with a carrier frequency preset as $f_C = 6000Hz$.

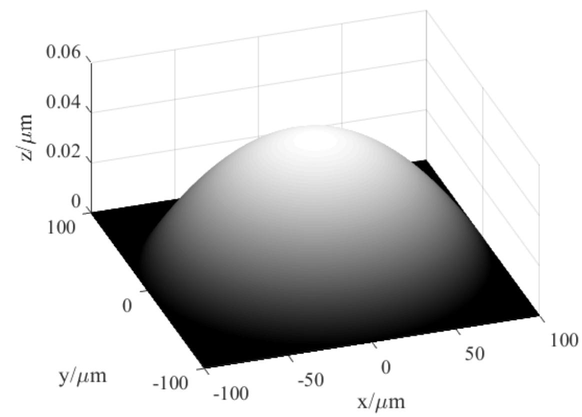

Figure 5. The spherical curve surface topography.

After scanning with a speed of $20\mu m/s$ from the top, the equivalent displacement is shown as in figure 6(a), and the retrieving displacement is shown as in figure 6(b).

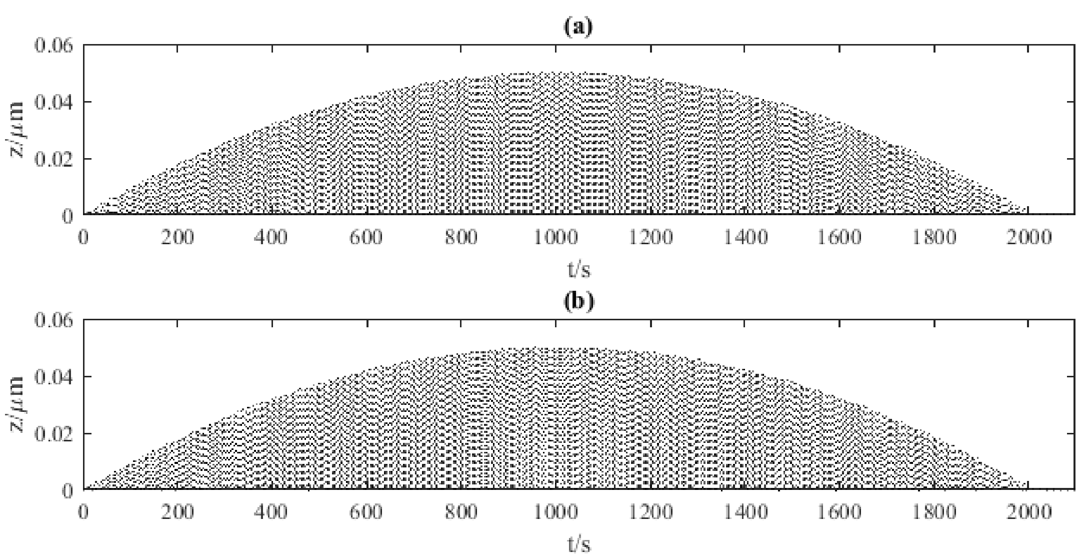

Figure 6. (a) equivalent displacement of spherical curve surface; (b) retrieving displacement of spherical curve surface.

By re-order and smoothing process, we can re-establish the profile of the arbitrary surface, as shown in figure 7.

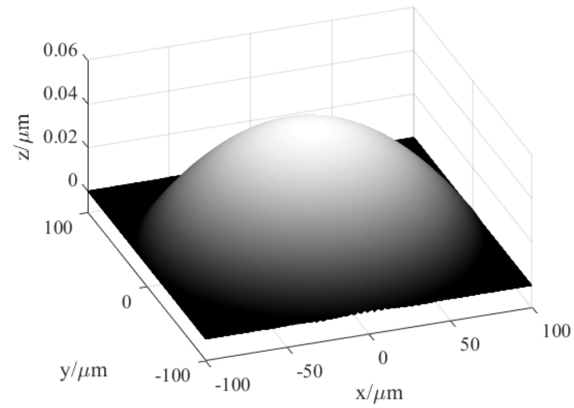

Figure 7. The retrieving spherical curve surface.

3.2 Simulation results for the surface with arbitrary topography

Suppose the measured surface as an arbitrary surface with a radius of curvature satisfying the functional distribution:

$$z(x,y) = (2\times10^{-6}\times x^3 + 2\times10^{-6}\times y^3 + 10^{-6}\times x^2 + 10^{-5}\times y^2 + 5\times10^{-5}\times x + 3\times10^{-5}\times y)/10 \tag{7}$$

where $x, y \in (-100\mu m, 100\mu m)$. The profile of the arbitrary surface is as shown in figure 8.

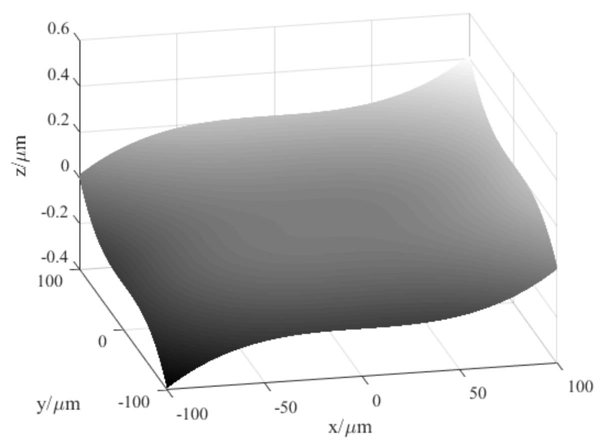

Figure 8. The asymmetrical curve surface topography.

After scanning, the equivalent displacement is shown as in figure 9(a), and the retrieving displacement is shown as in figure 9(b).

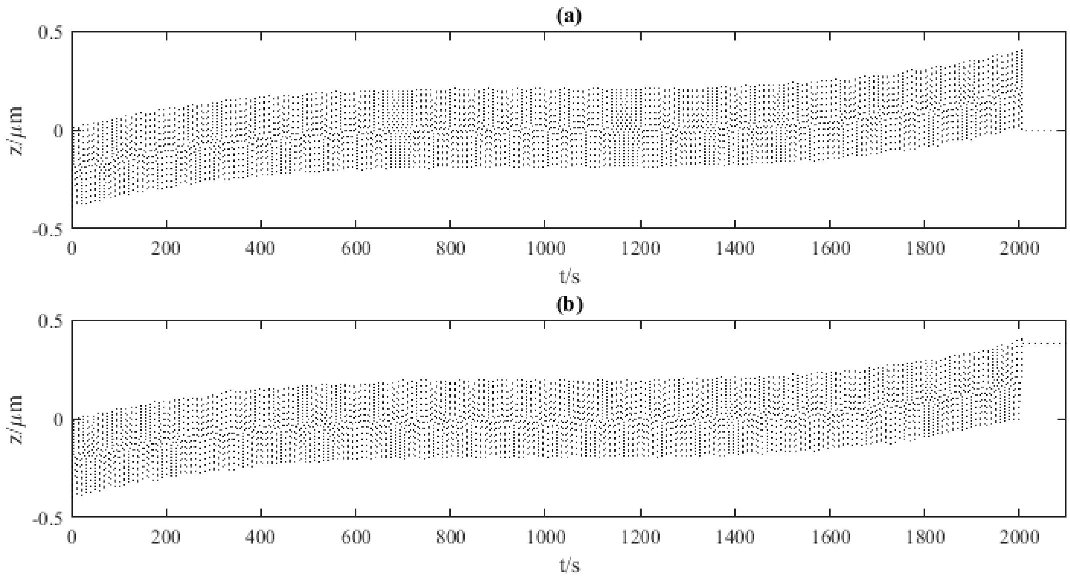

Figure 9. (a) equivalent displacement of arbitrary surface; (b) retrieving displacement of arbitrary surface.

By re-order and smoothing process, we can re-establish the profile of the arbitrary surface, as shown in figure 10.

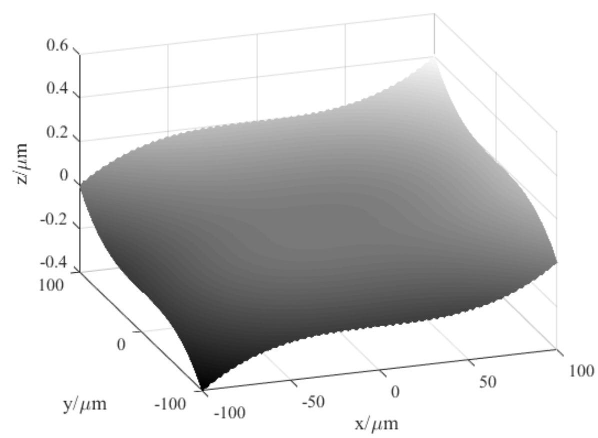

Figure 10. The retrieving arbitrary surface.

4. CONCLUSION

In this paper, we propose a new algorithm to improve measurement performance for an SMI-based profile sensing system. The improvement is achieved by introducing a reference signal to more accurately retrieve a varying phase signal, from which we can retrieve a micro-displacement to be measured using a traditional SMI system and then re-establish the profile. The proposed algorithm is implemented by Matlab. The simulation results verify the feasibility of the proposed method and shows it has high resolution and accuracy.

REFERENCES

[1] Sun, X., Wang, H., Liu, B. and Yu, Y., "Measurement of microsurface topography using a self-mixing optical configuration," Opt. Eng. 57(5), 051503 (2018).

[2] Fan, Y., Yu, Y., Xi, J. and Chicharo, J. F., "Improving the measurement performance for a self-mixing interferometry-based displacement sensing system," Appl. Opt. 50, 5064-5072 (2011).

[3] Giuliani, G., Norgia, M., Donati, S. and Bosch, T., "Laser diode self-mixing technique for sensing applications," Appl. Opt. 4, S283-S294 (2002).

[4] Bosch, T., "An overview of self-mixing sensing applications," in Proceedings of IEEE Conference on Optoelectronic and Microelectronic Materials and Devices, 385-392 (IEEE, 2004).

[5] Scalise, L., Yu, Y., Giuliani, G., Plantier, G. and Bosch, T., "Self-mixing laser diode velocimetry: application to vibration and velocity measurement," IEEE Trans. Instrum. Meas. 53, 223-232 (2004).

[6] Donati, S., Norgia, M. and Giuliani, G., "A review of self-mixing techniques for sensing applications," in Proceedings of the 17th Annual Meeting of the IEEE Lasers and Electro-Optics Society 261, 260-261 (2004).

[7] Donati, S., "Developing self-mixing interferometry for instrumentation and measurements," Laser Photonics Rev. 6, 393-417 (2012).

[8] Donati, S., Hwang, S. K., "Chaos and high-level dynamics in coupled lasers and their applications," Progress in Quantum Electronics, 2012.

[9] Yu, Y., Giuliani, G. and Donati, S., "Measurement of the linewidth enhancement factor of semiconductor lasers based on the optical feedback self-mixing effect," IEEE Photon. Technol. Lett. 16, 990-992 (2004).

[10] Yu, Y., Xi, J. and Chicharo, J. F., "Measuring the feedback parameter of a semiconductor laser with external optical feedback," Opt. Express 19, 9582-9593 (2011).

[11] Wang, M., "Fourier transform method for self-mixing interference signal analysis", Optics & Laser Technology 33, 409-416 (2001).

[12] Guo, D., Wang, M. and Tan, S., "Self-mixing interferometer based on sinusoidal phase modulating technique," Opt. Express 13, 1537-1543 (2005).