Optics Communications 340 (2015) 141–150

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Self-mixing vibration measurement using emission frequency sinusoidal modulation

Yufeng Tao, Ming Wang*, Dongmei Guo, Hui Hao, Qiang Liu

Jiangsu Key Laboratory on Opto-Electronic Technology, Department of Physics Science and Technology, Nanjing Normal University, Nanjing 210023, China

ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form
29 October 2014
Accepted 30 October 2014
Available online 12 November 2014

Keywords:
Laser self-mixing
Vibration measurement
Sinusoidal frequency modulation

ABSTRACT

In this paper, a simplified phase demodulation scheme is applied to recover vibration trail on a laser self-mixing interferometer for noncontact vibration measurement. The emission of semiconductor laser diode is modulated by injecting sinusoidal wave, and corresponding interference signal is a quasi-sinusoid wave. The vibration mathematical model for semiconductor laser diode is theoretically educed from basic self-mixing theory, the variation of target is converted into phase information. The simulation of demodulation algorithm and standard deviation are presented and the reconstructed waveform displays a desirable consistence with various moving trails. Following the principle, a minimum experimental system is established and position variation of the target mirror driven by voltage signal is translated into phase shifts, feedback is controlled at weak level during experiment, Fourier transform is implemented to analyze phase information. The comparisons of both amplitude and velocity with a Germany Doppler vibrometer are performed to testify vibration model, the error of proposed demodulation method is less than 30 nm and achieve a high accuracy in vibration frequency. The experimental results indicate the traditional phase technology can be applied on complex optical power signal after adaption providing a feasible application prospects in industrial and scientific situation with an inexpensive semiconductor laser.

1. Introduction

The laser self-mixing interference technology is a rising sensing technology, which has the features of compact, self-aligning and independent of optical coherent lengths compared to other laser interference. Characteristics of the self-mixing semiconductor laser is determined by external cavity length, feedback level, injecting current and linear enhancement factor in Refs. [1–5]. Lang and Kobayashi explained laser self-mixing effect firstly by solving basic laser rate equations in Ref. [6] which is origin of three mirrors model in Ref. [7] for analysis of SMI proposed by Groot. Varied work statuses of semiconductor on different feedback conditions systematically is studied by Tkach and Chraplyvy in Ref. [8]. Subsequent researches demonstrates the conclusion that weak feedback level can avoid mode hopping and coherent quenching in Refs. [9,10].

Due to importance of measuring displacement or vibration in self-mixing based sensing system, the estimation or measurement of feedback parameters of semiconductor laser with external optical feedback has been reported in Refs. [11–13]. Typically, these estimation approaches are based on data fitting techniques to decrease deviations between observed and calculated data samples. Until 2011, Yu.Y enlarges the range of C up to 10 by analysis phase condition of SMI in frequency domain in Ref. [14].

Because of compact-structure and easily-alignment, the optical sensor and interferometer using self-mixing laser diode (SM-LD) have been applied pervasively in Refs. [15,16] to measure moving or rotating objects and fluid velocity. The Doppler vibrometer and displacement sensor based on self-mixing semiconductor laser have been reported in Refs. [17,18]. In various industrial situations the micro-displacement or vibration are measured by self-mixing laser technology for checking resonant frequency, linearity of instrumentation or micro-electro-mechanical system, which promotes the development of self-mixing laser interferometer with high precision in last half century in Refs. [19–21]. The analog electrical output or PC-display of displacement visible make measurement more real-time and visible.

To further improve the immunity of self-mixing signal to optical and electronic noise, frequency modulation technology is introduced in semiconductor modulation. When injecting current exceeds threshold of laser diode, the light intensity is linear to pump current. At early stage of frequency modulation, a triangle wave current is injected into semiconductor laser diode for modulation, SMI intensity signal detected by internal PD is disposed by

* Corresponding author.
E-mail address: wangming@njnu.edu.cn (M. Wang).

http://dx.doi.org/10.1016/j.optcom.2014.10.071
0030-4018/© 2014 Published by Elsevier B.V.

differential electronics to remove carrier, thus, the fringe counting technology in Refs. [22,23] is used to retrieve the motion rail, obtaining accuracy of$\lambda/2$in Ref. [24] in wide frequency range. The digital demodulation process can be downloaded into DSP module forming a portable vibrometer in Ref. [25]. In recent years, the sinusoidal wave is injected into semiconductor laser as a new modulation, the Doppler velocimetry in Ref. [26] and Fabry–Perot interferometric vibration displacement sensor in Ref. [27] are both established by modulating laser sources sinusoidal showing a vigorous vitality in precise measurement.

With the introduction of EOM in Ref. [28] into self-mixing interferometer, the quick-FFT in Ref. [29] combining with phase demodulation technology in Refs. [30,31] providing the most competitive precision catches eyes of many researchers. In demodulation precision, the harmonics-analysis in Ref. [32] and PGC algorithm in Ref. [27] show the same sensitivity of $\lambda/4\pi$ theoretically, after amendment in program, the sinusoidal phase-shifting self-mixing interferometer laser gets further development with nanometer accuracy of $\lambda/50$in real-time micro-displacement measurement with support of computer technology in Refs. [32,33].

In this paper, a sinusoidal frequency modulating interferometer on a laser diode is proposed, which gets a considerable cost-down with absence of any modulator in modulation. Regardless of laser intensity, the fundamental and first harmonics are obtained by filters, thus, a simplified phase demodulation algorithm is used to reconstructed moving trail, the whole algorithm is implemented in time-domain. We organized this paper as follows: first section demonstrates measurement theory of sinusoidal frequency modulation and demodulation process. Second section presents simulation and error analysis under sampling. Third section describes the experiment parameters, setup, results and comparison with OFV5000.

2. Theory

2.1. Optical principle

As illustrated in Fig. 1, when only direct voltage is exerted on the driven-electronics of laser diode (LD) packed with photo diode, light emission from LD focus on target through lens module. The basic theoretical model is as follows:

$$I(t) = I_0(t)[1 + m\cos(\varphi_F(t)]\varphi_F(t)$$
$$= \varphi_0(t) - C\sin[\varphi_F(t) + k]k$$
$$= \arctan(\alpha)C$$
$$= \varepsilon(1 - r_2^2)\frac{r_3}{r_2}\frac{(L_0 + \Delta L)}{nl}\sqrt{1 + \alpha^2} \quad (1)$$

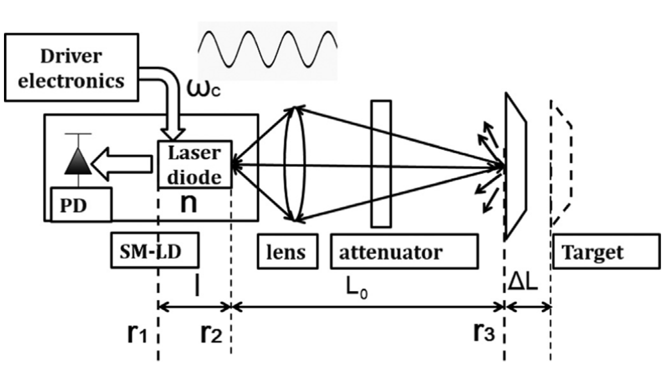

Fig. 1. Typical schematic of the laser diode self-mixing interference system.

Where the $I(t)$, $I_0(t)$ stand for the optical power with feedback and laser power, the middle equation about φ is phase condition of SMI, r_1, r_2, r_3 are reflection coefficients of laser end, laser head and target mirror, C is feedback level, α is the line width enhancement factor, n is the refractive index of material of laser cavity, $_l$ is laser internal cavity length, $_L$ is external length, and ΔL is variation, ε is coefficient of coupling. Defining the parameters as follows:

$$\varphi_0(t) = \omega_0 t = 2\pi f_0(t), f_0(t) = c_{air}/\lambda_0, \varphi_F(t) = \omega_F t = 2\pi f_F(t)$$

ω_F, ω_0 are the angular frequencies of laser with and without feedback, c_{air} is speed of laser beam in air, extending phase condition of SMI, the optical signal can be expressed as:

$$I(t) = I_0(t)[1 + m\cos(\varphi_0(t) - C\sin[\varphi_0(t) - C\sin[\varphi_0(t) - C\sin[\ldots + k] + k] + k]] \quad (2)$$

In analysis of model and experiment, parameter C tells the operational mode of SMI system which is considered to operate in very weak optical feedback regime theoretically. When C is known, α can be calculated out. Assuming $\varepsilon=0.15$, $r_2=0.8$, $r_3=0.5$, $n=2.54$, $(L_0 + \Delta L/)l=8, C<0.1$, we can get $\alpha^2 < 0.0844$, k is a small constant. The experimental system feedback level is controlled artificially to ensure $C<0.1$. On the condition of very weak feedback level without modulation current$C\sin[\varphi_F(t) + k] \ll \varphi_0(t)$, so $\varphi_F(t) \approx \omega_0 t = 2\pi f_0$, we express optical power of SMI approximatively as below:

$$I(t) = I_0(t)[1 + m\cos(2\pi f_0(t))] \quad (3)$$

When a sinusoidal current is simultaneously exerted on laser, optical power and laser frequency are both modulated and expressed as below:

$$I_0(t) = I_0 + \beta\Delta B(t) f_0(t) = f_0 + \Delta f = f_0 + \gamma\Delta B(t) \quad (4)$$

whereβ is current modulation depth, γ is frequency modulation depth,$\Delta B(t)$ is injecting current value,I_0 and f_0 are initial optical power and laser frequency. The external cavity length is expressed as$L(t) = L_0 + \Delta L(t)$, three mirror model is written as below:

$$I(t) = I_0(t)[1 + m\cos(2\pi f_0(t)\frac{2L(t)}{c_{air}})] \quad (5)$$

Where $2L(t)$means laser light makes a round trip in external cavity, m is modulation depth. Combining Eqs. (4) and (5), the model of self-mixing interference is written as below:

$$I(t) = [I_0 + \beta\Delta B(t)][1 + m\cos(4\pi(f_0 + \gamma\Delta B(t))\frac{L_0 + \Delta L(t)}{c_{air}})] \quad (6)$$

The sinusoidal current variation$\Delta B$and sinusoidal vibrationΔL can be expressed as followed:

$$\Delta B(t) = B\cos(\omega_c t)\Delta L = D\cos(\omega_m t) \quad (7)$$

Where B and D are the amplitudes of current and vibration, ω_c and ω_m are angular frequencies of modulation signal and vibration signal, extend Eq. (6) in detail:

$$I(t) = [I_0 + \beta B\cos(\omega_c t)]$$
$$[1 + m\cos(4\pi(f_0 + \gamma B\cos(\omega_c t))(\frac{L_0 + D\cos(\omega_m t)}{c_{air}})] \quad (8)$$

Comparing with initial external cavity length, the variation of vibration is small, $(4\pi/c_{air})\lambda BD\cos(\omega_c t)\cos(\omega_m t)$is an relative extreme minimum being neglected. The output optical power can be