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Vibration measurement based on Multiple Self-Mixing Interferometry

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ABSTRACT

We propose a novel algorithm for Multiple Self-Mixing Interferometry (MSMI). The algorithm is able to measure nanometer scale vibration by the power spectrum analysis. In the paper, the principles of the method are introduced in detail. The experimental setup has been built. The validity of the proposed algorithm was confirmed by conducting a series of experimental measurements at different reflection times, feedback factors, and vibrational frequencies using PZT as a reference. Experimental results showed that the method can quickly demodulate parameters of vibration and good correspondence between theory and experiment. The proposed algorithm, thus, furnishes nanometer measurements with a very high resolution using a self-aligned, cost effective and compact experimental setup.

1. Introduction

Self-Mixing Interferometry (SMI) is an emerging and promising optical measurement technology[1,2]. When a portion of the laser output light is reflected or scattered by the vibrating target and returned to the laser cavity. The output light and returned light form the optical feedback effect, which changes the output power and frequency of the laser. This phenomenon is known as SMI. SMI has $\lambda/2$ fringe resolution, which is the same accuracy as that of the traditional double-beam interference. Laser output power changes an interference fringe when the external target moves by half a wavelength. SMI measuring device has features such as a simple structure, easy collimation, non-contact, and easy integration. Therefore, SMI has been widely used in velocity [3,4], as well as in the measurement of vibration [5–9], distance [10–12], displacement [13–17], and biomedicine [18–20], three-dimensional imaging [21–23] and laser parameters [24–27], and other measuring fields. To improve the accuracy of measurement, many signal-processing algorithms have been proposed, such as the phase unwrapping algorithm [13,28] and the Fourier analysis algorithm [7,29,30]. These algorithms can improve accuracy from $\lambda/10$ to $\lambda/50$.

When SMI occurs in an asymmetrical cavity, the light and vibrating target are not strictly vertical. The light will experience multiple reflections between the vibrating target and the laser. In such case, the number of interference fringes doubles or even increases three or four times. This phenomenon is called Multiple Self-Mixing Interferometry (MSMI). In 1996, Ref. [31] reported that the phenomenon of double interference fringes could be produced through the asymmetrical cavity of a laser. In Ref.[32], vertical-cavity surface-emitting lasers were used to observe reflections that occurred thrice between a target and a laser with an interference fringe resolution of $\lambda/6$. Many researchers have studied the MSMI phenomenon, however, few studies have focused on MSIM demodulation algorithms. The interference fringe resolution of MSMI is several times higher than that of SMI; thus, it is important to find a MSMI demodulation algorithm for improving the accuracy of measurement instruments.

This study focuses on a demodulation algorithm of MSMI and adopts a power spectrum analysis algorithm to demodulate the amplitude and frequency of a vibrating target. Therefore, several aspects are addressed as follows. First, the principles of MSMI are briefly explained. Second, a power spectrum analysis algorithm is proposed, and its processing procedure is described in detail. Finally, the algorithm is validated through experimental data.

2. Theory of multiple self-mixing interferometry

The MSMI formation process is shown in Fig. 1 [31]. r_1, r_2, are the amplitude reflectivity of the laser inner cavity. r_3 is the amplitude reflectivity of the laser external cavity. r_3 is the reflectivity of vibrating target too. If a vibrating target has a slight inclination angle θ with the optical axis, then the laser, lens, and vibrating target will constitute an asymmetrical external cavity. When light is emitted from the inner laser cavity as it travels along the optical axis to the vibrating target through the lens, the light and the target reflector are not strictly vertical, and thus, the reflected light is not returned into the laser inner cavity. However, the light may

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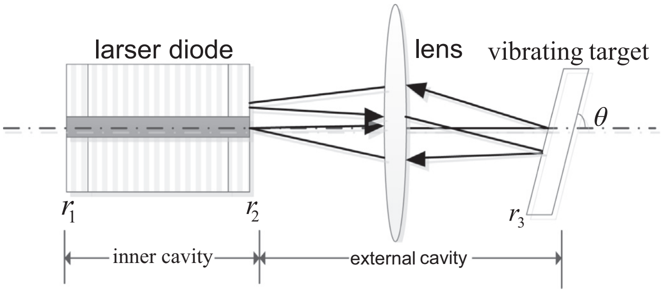

Fig.1. MSMI principle.

be reflected to the laser edge to form a second reflection. The second emitted light reflects onto the vibrating target through the lens and finally enters the laser inner cavity. Light travels multiple reflections between the vibrating target and the laser to form MSMI. SMI and MSMI fringes were shown in Fig. 2. An SMI wave is shown in Fig. 2(1). In Fig. 2(2), light is reflected twice (2-MSMI), and the optical path is twice as long as that in SMI; thus, the interference fringe resolution is λ/4. In Fig. 2(3), light is reflected thrice (3-MSMI), and the optical path is thrice longer than that in SMI; therefore, fringe resolution is $\lambda/6$. In Fig. 2(4), light is reflected four times (4-MSMI), and the optical path is four times as long as that in SMI; hence, fringe resolution is $\lambda/8$.

SMI theory has been described by many researchers and is briefly explained as follows [33]. We will derive the MSMI power equation based on SMI theory. An optical feedback induces a change in the output power of a laser. The optical output power $p(t)$ with feedback can be written as follows:

$$p(t) = p_0[1 + m\cos(2\pi\nu\tau)], \tag{1}$$

where p_0 is the output power of the laser without feedback, m is the modulation index, $2\pi\upsilon\tau$ is the laser output phase with feedback, υ is the light frequency, and τ is the round-trip time in the external cavity.

The MSMI power equation can be derived from Eq.(1). The distance of the laser to the vibrating target is assumed as l; thus, light is reflected k times between the laser and the vibrating target. τ can be given by

$$\tau = \frac{2kl}{c}, \tag{2}$$

where k is number of reflection times occurring between the laser and the vibrating target.

By combining Eqs. (1) and (2), and based on $c=\nu\lambda_S$, the MSMI output power $p(t)$ can be written as

$$p(t) = p_0\left[1 + m\cos\left(\frac{4k\pi l}{\lambda_s}\right)\right], \tag{3}$$

where λ_S is the laser wavelength with feedback.

3. Proposed power spectrum algorithm

The vibrating target performs a simple harmonic motion, and the frequency and amplitude are f_0 and A_0, respectively. The initial phase is φ and the initial distance between the laser and the vibrating target is l_0; hence, the vibrating target motion equation l can be expressed as

$$l = l_0 + A_0\sin(2\pi f_0 t + \varphi), \tag{4}$$

If multiple reflections are neglected, the coupling coefficient of the external cavity k_{ext} can be expressed as follows [34]:

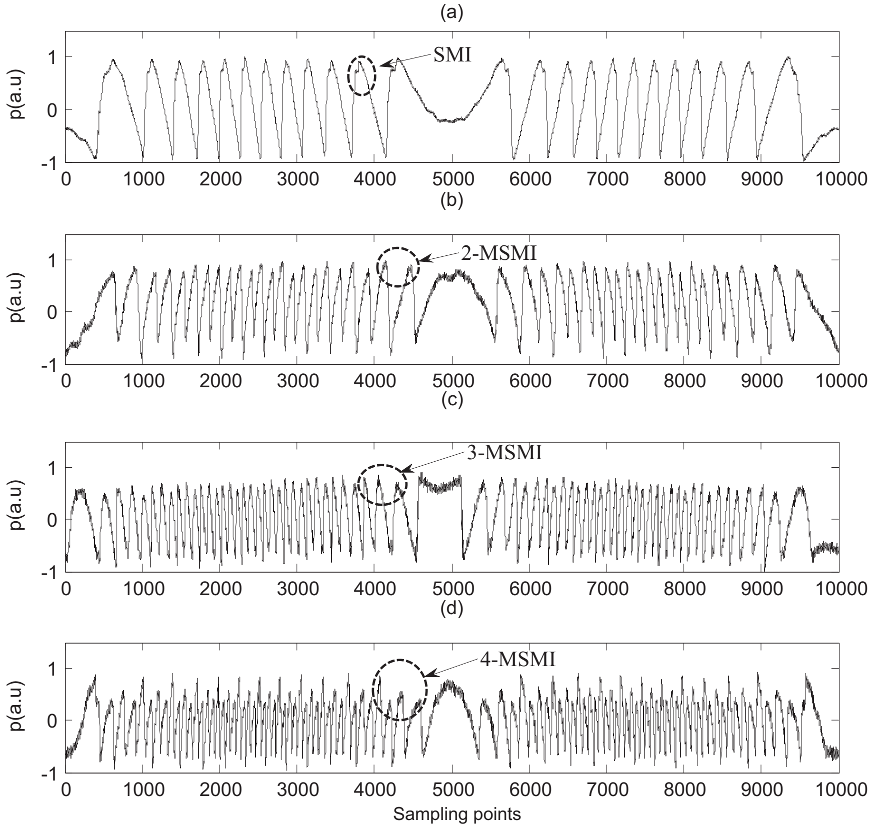

Fig.2. SMI and MSMI fringes.