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Polarization-standing-wave interferometer for displacement measurement

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HIGHLIGHTS

- Optical standing wave can be observed by the single layer of spherical silicon dioxide nanoparticles.
- Polarization phase quadrature technique is implemented for the phase demodulation and the displacement measurement.
- Polarization standing wave interferometer has millimeter-scale measurement range with nanometer-scale resolution.

ARTICLE INFO

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ABSTRACT

An optical standing-wave interferometer using a polarization technique for displacement measurement is proposed. An ultra-thin scattering plate is inserted into the optical standing-wave field, which is built by the interference of the forward- and backward-propagating light beams. By means of detecting the phase variations of the scattered light from the scattering plate with the polarization phase quadrature technique, the displacement can be determined precisely. The experimental results demonstrate that this polarization-standing-wave interferometer can measure displacement on a scale of tens of millimeters with nanometer-scale resolution. The periodic nonlinear error caused by the multi-beam interference is also detailed.

1. Introduction

To achieve high performance, precision positioning and displacement measurement become more important and significant requirements in science, engineering, and industrial applications, such as metrology instruments, nanotechnology, biotechnology semiconductors, and precision manufacturing. The laser interferometer has been popularly applied for highly precise displacement measurement, because it offers high measurement resolution and a wide dynamic measurement range. The two-beam interferometer (TBI), such as the Michelson or Mach–Zehnder type, is the most common displacement sensing technique. In TBI, one or two beamsplitters are used to split the light beam into two paths and combine the portions of two different beams into one path to create the interference. The displacement can be obtained by analyzing the interference fringes with homodyne [1], heterodyne [2,3], or polarization detection [4]. Because of the two-optical-arms configuration, and the fact that several optical components are used, it is difficult to reduce the size of the TBI apparatus. On the other hand, the single-beam interferometer (SBI) can have a compact size. The conventional SBI or common-optical-path interferometer [5–7] can characterize the optical property of the testing material by analyzing the phase difference between the S- and P-polarization of the beams, which pass through or reflect from the testing material. However, it is not suitable for measuring the displacement of a moving target because of the short dynamic range.

Recently, the SBI standing-wave sensing technique has been developed and applied for displacement measurement [8–10]. The key device in the standing-wave sensing technique is the transparent thin photodiode, which has a highly compact size. In order to achieve high optoelectronic performance, the thickness of the stacked layer of the transparent thin photodiodes must be well controlled with a highly complex semiconductor manufacturing process. Dong et al. [11] proposed a novel SBI with photonic metamaterial for detecting the intensity distribution of the standing wave, and applied it to displacement measurement. Their experiment was successfully implemented with the standing waves in the microwave range, and a measurement resolution of several millimeters was verified.

By means of detecting the scattering light from the single-layer SiO_2 nano-sphere plate, we developed an SBI with an optical standing-wave sensing technique, and applied it to displacement measurement [12] with the phase quadrature technique. In our previous work, the phase quadrature technique was based on detecting the scattering light from two separated scattering plates. However, the distance between the two separated scattering plates must be well controlled to have exact

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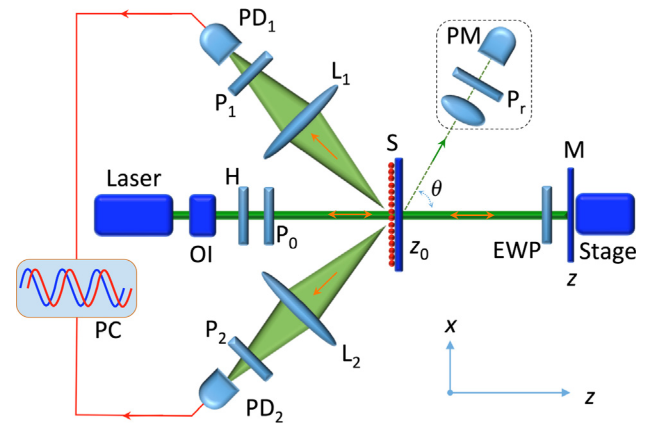

Fig. 1. Schematic of the polarization-standing-wave interferometer.

quadrature phases. Moreover, using two scattering plates reduced the signal-to-noise ratio of the system. In this paper, on the basis of single-layer nano-sphere scattering, we propose a polarization phase quadrature technique to analyze the phase variation of the optical standing wave for displacement measurement.

2. Principles

2.1. Polarization interference of the standing wave

Fig. 1 shows a diagram of the polarization-standing-wave interferometer (PSWI). The linear polarized laser beam passes through an optical isolator OI, single-layer SiO_2 nano-sphere scattering plate S, and eighth-wave plate EWP, and then is reflected back by the mirror M. The standing-wave field is built between the optical isolator and the mirror. Here we assume that the positions of the optical isolator, scattering plate, and mirror are at 0, z_0, and z, respectively. Let the polarization angle of the forward propagating laser beam be at 45° with respect to the x-axis. According to the Jones calculation, the Jones vector E_R of the forward laser beam at position z_0 can be expressed as [8,12]

$$E_R = E_r\begin{pmatrix}1\\1\end{pmatrix}\exp\left(i\frac{2\pi}{\lambda_0}z_0 - i\omega t\right), \tag{1}$$

where ω and λ_0 are the optical frequency and wavelength of the laser beam, respectively. Because the backward propagating laser beam passes through the eighth-wave plate twice, the polarization state of the laser beam is changed to circular. Its Jones vector E_L can be expressed as

$$E_L = E_l\begin{pmatrix}1\\i\end{pmatrix}\exp\left(-i\frac{2\pi}{\lambda_0}(z_0-2z) - i\omega t + i\pi\right). \tag{2}$$

These two beams interfere with each other and two types of standing waves are built in the optical axis because of the polarization effect. They are horizontally and vertically polarized standing waves, respectively. As shown in Fig. 1, the ultra-thin scattering plate S is inserted in the optical path to scatter the optical standing waves. The scattered light is collected by the lenses L_1 and L_2, filtered by the horizontal and vertical polarizers P_1 and P_2, and then received by the photodetectors PD_1 and PD_2. According to the Jones calculation, the interference electric field on the photodetectors PD_1 and PD_2 can be written as

$$E_1 = P_1(0^\circ)(E_R + E_L), \tag{3}$$

and

$$E_2 = P_2(90^\circ)(E_R + E_L), \tag{4}$$

where P_1 (0°) and P_2 (90°) are the Jones matrixes of the polarizers with the transmission axes of 0° and 90°, respectively. The light intensities on the photodetectors are proportional to the absolute square of the resulting electric fields. However, because of the unbalanced amplitudes of the forward and backward beams ($E_r \neq E_l$), the thickness effect of the scattering plate [9], and speckle effect [13], the contrast V of the interference intensities must be smaller than 1. These two interference intensities can be expressed as

$$I_1 \propto |E_1|^2 = I_{10}[1 - V_1\cos(\phi + \phi_s)], \tag{5}$$

and

$$I_2 \propto |E_2|^2 = I_{20}[1 - V_2\sin(\phi + \phi_s + \varphi)], \tag{6}$$

where

$$\phi = 4\pi(z_0 - z)/\lambda_0, \tag{7}$$

is the phase variation caused by the displacement z_0 or z. $I_{10,20}$ and $V_{1,2}$ are the main intensity and contrast of the optical standing wave, respectively. ϕ_s is the initial phase that results from the thickness effect of the scattering plate [12]. φ denotes the non-orthogonal error (NOE), which may result from the polarization mixing of the interference beams and misalignment of polarization components [14,15]. Eqs. (5) and (6) indicate, obviously, that except for the NOE φ, these two signals I_1 and I_2 are phase quadrature, and can be used to determine the displacement z_0 or z. However, the unbalanced DC (I_{10} and I_{20}) and AC (V_1I_{10} and V_2I_{20}) components of these two sinusoidal signals and the NOE φ result in periodic nonlinear error (PNE) of the displacement measurement. The unbalanced DC and AC mainly come from background light disturbance, unequal gain of the photodetectors, and geometrical errors.

2.2. Interference signal calibration

Before starting the displacement measurement, the two sinusoidal signals in Eqs. (5) and (6) must be calibrated to eliminate the PNE. The unbalanced DC and AC and the NOE φ can be calibrated by using our previous work [12] and the orthogonalization technique [14], respectively. The calibration process is described as follows. First, the mirror is provided an increasing displacement. The interference signals I_1 and I_2 oscillate with increasing displacement as shown in Fig. 2(a). The curve in Fig. 2(b) shows the Lissajous patterns of these two uncalibrated signals. The DC (I_{10} and I_{20}) and AC (V_1I_{10} and V_2I_{20}) terms of these two

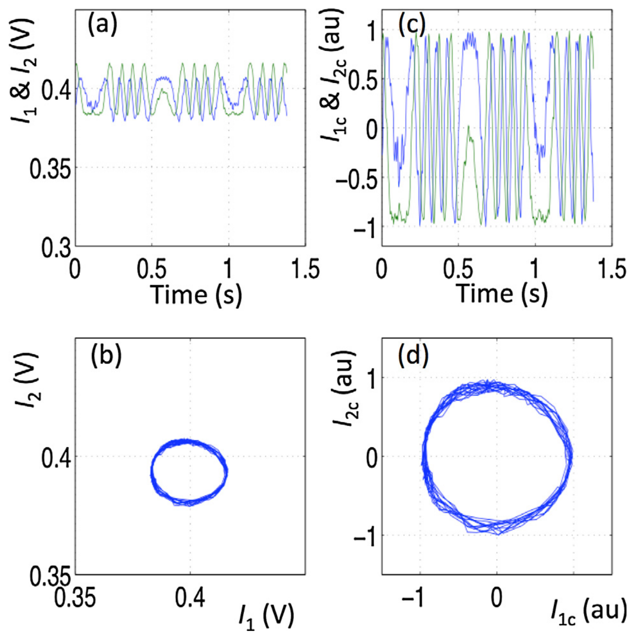

Fig. 2. (a) Original and (c) calibrated interference signals. Lissajous patterns of the (b) original and (d) calibrated interference signals.