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Invited Paper

Synthetic-wavelength self-mixing interferometry for displacement measurement

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ABSTRACT

A simple synthetic-wavelength self-mixing interferometer is proposed for precision displacement measurement. Choosing the frequency difference of the orthogonally polarized dual frequency He–Ne laser appropriately, we introduce synthetic wavelength theory into self-mixing interference principle and demonstrate a feasible optical configuration by simply adjusting the optical design of self-mixing interferometer. The phase difference between the two orthogonally polarized feedback fringes is observed, and the tiny displacement of the object can be measured through the phase change of the synthetic signal. Since the virtual synthetic wavelength is 10^6 times larger than the operating wavelength, sub-nanometer displacement of the object can be obtained in millimeter criterion measurement without modulation, demodulation and complicated electrical circuits. Experimental results verifies the synthetic wavelength self-mixing interferometer's ability of measuring nanoscale displacement, which provides a potential approach for contactless precision displacement measurement in a number of scientific and industrial applications.

1. Introduction

In recent years, laser self-mixing effect has been widely investigated and applied in the field of displacement measurement [1–4] due to its inherent simplicity, compactness and self-alignment, as well as the same fringe resolution as in traditional two-beam interferometry [5–7]. The self-mixing interferometer is able to measure displacement very precisely when the displacement is more than half-wavelength, which plays important role in scientific application for large-scale displacement measurement [8,9]. With the development of nano-electro-mechanical systems (NEMs) technique, the motion of the mechanical component of such tiny devices has reduced to nanometer-scale. As the most competitive technique for non-contact displacement measurement, extending the resolution of the self-mixing interferometer into sub-nanometer range is highly desirable [10,11]. However, when the displacement is smaller than half-wavelength, the structure of self-mixing interferometer would become more complicated and expensive because of the extra careful design of an optical system and complicated electrical circuits imposed on it. In this case, to simplify its structure, reduce the cost and achieve high resolution, it is essential to introduce a new subdivision method to make full use of merits of the self-mixing interferometer.

Compared with the other subdivision methods, the approach of synthetic wavelength can be applied more easily to improve resolution by simply adjusting the optical configuration of Michelson interferometer; thereby avoiding the tedious modulation, demodulation and complicated electrical circuits. Synthetic wavelength measurements were first reported in 2002, where two individual wavelengths of light have been employed to measure small distances relative to the 'reduced' wavelength [12,13]. Through this dual-wavelength interferometric technique, sub-nanometer measurement accuracy has been achieved. However, when applied in NEMs, the cooperative mirror in Michelson interferometer such as cube-corner retro-reflector necessitated in the technique could not suit the tiny size of such microstructures any more.

Therefore, in this paper, a simple scheme based on the synthetic wavelength self-mixing interferometer (SSI) for high-precision non-contact displacement measurement is proposed. Previous researches on the self-mixing interference effect in orthogonally polarized dual frequency He–Ne laser show that the mode competition will affect the phase relationship between the two self-mixing interference signals. If the frequency difference between two modes is greater than the line width of homogeneous broadening gain curve of laser (about 100–300 MHz), the phase relationship of two intensity modulation curves will be mainly determined by phase difference of two modes, and mode

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competition can be neglected [14]. In this case, the intensity curves of the two orthogonal modes are independent and synthetic wavelength configuration can be brought into the self-mixing interferometer to get rid of the disadvantage of complicacy and high cost in non-contact tiny displacement measurement. An experimental system is designed and nanometer measurement experiment is conducted subsequently. In this system, an orthogonally polarized dual frequency He–Ne laser with a frequency difference of 1 GHz is employed in optical configuration to avoid mode competition. Experimental result of nanometer measurement is in conformity with the theoretical value, which validates the principle and indicates that the SSI can measure nanometer displacement with a modest sampling rate within a range of 500 nm. The sources of error influenced on the measurement accuracy and resolution are discussed and evaluated. The analysis shows a new method of nanometer displacement measurement in self-mixing interference is realized.

2. Theoretical analysis

Fig. 1 shows the theoretical schematic diagram of synthetic wavelength self-mixing interferometer. The reflectivity of the rear and front mirrors of laser are r_1 and r_2, respectively. M1 and M2 are plane mirrors with same reflectivity of r. M1, M2, together with the front mirror form dual feedback external cavities, whose lengths are present as $L + d$ and $l + d$.

The illuminant displayed in Fig. 1 is a birefringent dual frequency He–Ne laser. As is known to us all, light entering and passing through a quartz crystal will be decomposed into two orthogonal elliptically polarized components, ordinary and extraordinary beams, having different transmission velocities. Experiments manifest that, the two polarization directions and phase difference are related to the angle and the projection of the activity vector on to the light traveling direction. Because of the existing of the phase difference, a single mode of a laser can be split into two orthogonally polarized modes [15,16]. Adjusting the angle, we get different frequency difference of the laser. As mentioned earlier, if the frequency difference between two modes is greater than the line width of homogeneous broadening gain curve of laser (about 100–300 MHz), burning holes of the two modes can be considered independent. Moreover, the self-mixing interference of one frequency does not confuse the other. Hence, self-mixing interference of a birefringent dual frequency He–Ne laser can be simply theoretically described in this case.

In the basic theory of self-mixing interferometry modeled as a three-mirror Fabry–Perot etalon [17], the oscillating condition of a dual frequency laser with self-mixing interference can be given as [18–20]

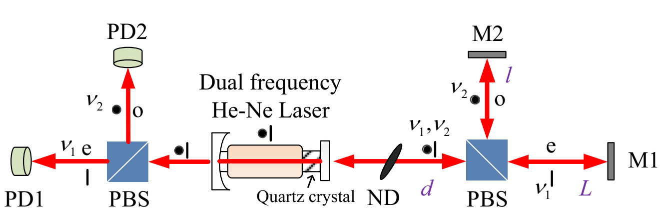

Fig. 1. Theoretical diagram of synthetic self-mixing interference. M1 and M2, plane mirrors; PBS, polarizing beam splitter cube; ND, Neutral Density Filter;PD1 andPD2, photo detectors.

$$\begin{cases} r_1 r_2\left[1 + \dfrac{r\left(1 - r_2^2\right)}{r_2} e^{i\omega_e\tau_e}\right] e^{(G_e - a_e)} e^{i\omega_e\tau} = 1 \\ r_1 r_2\left[1 + \dfrac{r\left(1 - r_2^2\right)}{r_2} e^{i\omega_o\tau_o}\right] e^{(G_o - a_o)} e^{i\omega_o\tau} = 1 \end{cases}. \tag{1}$$

where G_e and G_o are the laser total normalized gains, a_e and a_o are the total normalized internal losses, ω_e and ω_o are the optical angular frequencies of e light and o light, τ is the laser beam round-trip time in internal cavity, τ_e and τ_o represent the laser beam round-trip time in external cavities. Since $r_1 > r$ and $r_2 > r$, both of r_1 and r_2 are approximate 1 and $r(1 - r_2^2)/r_2 \ll 1$, the normalized threshold gains change can be transformed as $\Delta G_e = -\ln\{1 + [r(1 - r_2^2)/r_2] e^{i\omega_e\tau_e}\} \approx \alpha_e \cos\varphi_1$ and $\Delta G_o \approx \alpha_o \cos\varphi_2$, where α_e and α_o are intensity optical feedback factors , $\varphi_1$and φ_2 denote the phase of the external cavity which are related to the instantaneous distance between the laser and the mirrors, as $\varphi_1 = \omega_e\tau_e = 4\pi(L + d)/\lambda_1, \varphi_2 = \omega_o\tau_o = 4\pi(l + d)/\lambda_2$. Based on the effect of multiple reflections in the external cavity [21], the steady-state fluctuations of the emitted optical power of the laser can be given as

$$\begin{cases} I_e = I_{e0}\left[1 + m_e \cos\varphi_1 \sum_{j=0}^{\infty} (-\eta_e)^j \cos(j\varphi_1)\right] \\ I_o = I_{o0}\left[1 + m_o \cos\varphi_2 \sum_{j=0}^{\infty} (-\eta_o)^j \cos(j\varphi_2)\right] \end{cases}. \tag{2}$$

where I_{e0} and I_{o0} represent the average intensities of two orthogonally polarized lights without optical feedback, η_e and η_o are the coupling coefficient , m_e and m_o are the undulation coefficient depending on intrinsic laser parameters and the reflectivity of the mirrors. Supposing that the self-mixing interferometry operates in the weak optical feedback regime, the frequency of laser is unperturbed [22] and the output intensities of two orthogonally polarized lights with self-mixing interference can be simplified as

$$\begin{cases} I_e = I_{e0}(1 + m_e\cos\varphi_1) \\ I_o = I_{o0}(1 + m_o\cos\varphi_2) \end{cases}. \tag{3}$$

Given $\Delta\varphi = \varphi_2 - \varphi_1$, $\Delta\varphi$can be written as

$$\Delta\varphi = 4\pi\left(\frac{d}{\lambda_3} - \frac{L}{\lambda_1}\right) + \frac{4\pi l}{\lambda_2}. \tag{4}$$

where $\lambda_3 = \lambda_1\lambda_2/|\lambda_2 - \lambda_1| = c/\Lambda$ is the synthetic wavelength (c and Λ represent the light velocity and frequency difference of two orthogonally polarized lights respectively). Supposing $C = 4\pi l/\lambda_2$ as a constant, Eq. (4) can be rewritten as $\Delta\varphi = 4\pi[(\Lambda\cdot d)/c - L/\lambda_1] + C$, where Λ and λ_1 are constants as system parameters, and C is set to zero in this work. To make the synthetic wavelength intuitive, we define a synthetic signal

$$I_s = m_s\cos\Delta\varphi = m_s\cos\left[4\pi\left(\frac{\Lambda\cdot d}{c} - \frac{L}{\lambda_1}\right)\right]. \tag{5}$$

Actually, I_s can be obtained from I_e and I_o by electronic method such as a multiplier, and m_s represents the coupling intensity coefficient. When L is fixed, we can just concern about the relationship between d and I_s, so the period of synthetic signal is λ_3. If the increment of L is set as ΔL, I_s will be changed as I_s'. So Eq. (5) can be written as

$$I_s' = m_s\cos\left[4\pi\left(\frac{\Lambda\cdot d}{c} - \frac{L + \Delta L}{\lambda_1}\right)\right]. \tag{6}$$

I_s' can be considered as the shifted signal of I_s. Given Δd as the shift of I_s, ΔL can be expressed by