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Self-mixing interferometry based on all phase FFT for high-precision displacement measurement

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ABSTRACT

Self-mixing interferometry is an extreme simple and compact laser technique to develop non-contact displacement sensors. In order to enhance the precision of this type of sensor, an improved FFT algorithm, based on all phase FFT instead of conventional FFT, has been proposed to provide a phase reference for self-mixing displacement measurement system which has only single light path and lacks reference. The principle and the experimental realization of the proposed algorithm have been presented. The operation mechanism utilizes all phase FFT, which can estimate the phase from signal accurately, to achieve phase reference when the external target is held stationary and then compensate this reference to the phase when the target starts to move. Resultant displacement value reflects the actual position of the target. Reconstruction errors are on the order of nanometers in the displacements ranging from 100 nm to 1 μm. Therefore, the proposed method can find application in displacement measurement in industrial and scientific environments.

1. Introduction

During the last decades, laser diode self-mixing interferometry (SMI) has been an emerging phenomenon which attracted a lot of attention from various research groups worldwide [1,2]. This phenomenon means that light emitted from the laser diode is back reflected or back scattered by a target in external cavity and a fraction of light re-enters into the laser cavity to mix with the internal lasing field [3,4]. Both the lasing frequency and output power of laser diode are modified by the reflected light which includes the moving information of the target. Analyzing the variation of output power or lasing frequency, the moving information of the target can be deduced. Therefore, SMI can be widely used in the sensors to detect distance, displacement, velocity, flow rate and vibration [5,6]. The measuring system based on SMI only consists of a laser diode and an external target, sometimes, a variable attenuator is added to the laser axis to adjust the intensity of the reflected light [7]. This simple and compact setup makes SMI a potential method superior to traditional interferometry and other optical measurement methods.

Recently, various methods have been proposed to process SMI signal to extract displacement information. Just like the traditional interferometry, displacement can be easily achieved by counting the fringes of SMI signal, but the resolution is limited to half of the wavelength [8]. So many researchers have attempted to explore novel approaches to analyze SMI signal. Donati from Italy deduced a set of formulas to quickly calculate the displacement of the target, however, the moving tendency of the target needed to be known primarily [9]. Usman Zabit designed a SMI fringe detecting method with adaptive threshold to achieve high accuracy and real-time measurement, but the method was very sensitive to noise and difficult to detect the displacement below half of the wavelength [10]. Phase analysis methods have been developed because of their high accuracy. Servagent used phase shift method to achieve accuracy of 65 nm at a distance less than 1 cm [11], but it needed phase shift crystal, which made light path more complex, in the external cavity. Ming Wang introduced FFT analysis method to process SMI signal and a resolution of $\lambda/50$ was achieved [8]. Nonetheless, in view of spectrum leakage, the phase got from FFT algorithm was not accurate. Absolute external cavity length is so difficult to measure with precision of nanometer that initial target position cannot be solved accurately. Therefore, the phase got from FFT algorithm does not directly correspond to displacement relative to the initial target position, and SMI phase detecting algorithm needs further research to make phase more practical and meaningful.

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In this paper, we propose an improved FFT algorithm based on all phase FFT which can suppress spectrum leakage and obtain phase accurately regardless of spectrum correction, at the same time, a reference phase corresponding to initial external cavity length is given to render the displacement relative to initial target position being solved directly and accurately. Section 2 presents the fundamental theory of SMI and all phase FFT. In Section 3, experimental results are shown, and related discussions are demonstrated in Section 4. At last, the conclusions are drawn in Section 5.

2. Theoretical analysis

2.1. Relationship between displacement and phase

The basic theory of SMI can be explained by two Fabry-Perot cavities model or time-delayed Lang-Kobayashi rate equations, as have been reported in abundant prior papers [12–14]. Optical feedback strength parameter has been defined by researchers as C [15]:

$$C = \left[\frac{L}{nl}\right] \cdot (1 - r_2^2) \cdot \left(\frac{r_3}{r_2}\right) \cdot \sqrt{1+\alpha^2} \quad (1)$$

here r_2 and r_3 are the amplitude reflection coefficients of laser diode facets and external target, l is the length of the laser cavity and L is the length of the external cavity, and α is the line width enhancement factor. Neglecting the multiple reflections in the external cavity and at very weak feedback regime ($C \ll 1$), the frequency and the emitted optical power in the presence of optical feedback can be expressed as [16]

$$2\pi(\nu_0 - \nu_F)\tau_{ext} = C \sin(2\pi\nu_F\tau_{ext} + \arctan\alpha) \quad (2)$$

$$P = P_0[1 + m\cos(2\pi\nu_F\tau_{ext})] \quad (3)$$

where P_0 and ν_0 are the optical power and lasing frequency without optical feedback, and m is the constant modulation coefficient. ν_F is the optical frequency of laser diode in the presence of feedback, τ_{ext} is the time of a circle of light beam in the external cavity.

From expression (2), we define that

$$\varphi_0 = 2\pi\nu_0\tau_{ext}, \varphi_F = 2\pi\nu_F\tau_{ext} \quad (4)$$

These two parameters separately mean phase without feedback and phase with feedback.

Emitted power of laser diode can be linearly modulated by the injection current [17]. So can the lasing frequency. One point must be taken into account is that the amplitude of injection current must be small enough so that the mode jump does not occur. Here a sawtooth like current tr(t) above the threshold current is used to modulate our laser diode, so that the output power is sawtooth like as well. Considering that the feedback strength is very weak($C \ll 1$), $\nu_F \approx \nu_0$ and $\varphi_F \approx \varphi_0$. Then with sawtooth current modulation, lasing frequency with feedback can be given [18]

$$\nu_F(t) = \nu_0 + \gamma\ \mathrm{tr}(t) \quad (5)$$

γ means the relationship between lasing frequency and modulation current with a unit Hz/mA. If the external target is moving with initial external cavity length L_0 and displacement d.

$$L(t) = L_0 + d \quad (6)$$

$$\begin{aligned}\varphi_F &= 2\pi\nu_F(t)\tau_{ext} = 2\pi[\nu_0 + \gamma\,\mathrm{tr}(t)]\frac{2(L_0+d)}{c} \\ &= \frac{4\pi}{c}[\gamma\,\mathrm{tr}(t)L_0 + \gamma\,\mathrm{tr}(t)d + \nu_0 L_0 + \nu_0 d] \quad (7) \\ &\approx \frac{4\pi}{c}[\gamma\,\mathrm{tr}(t)L_0 + \nu_0 L_0 + \nu_0 d]\end{aligned}$$

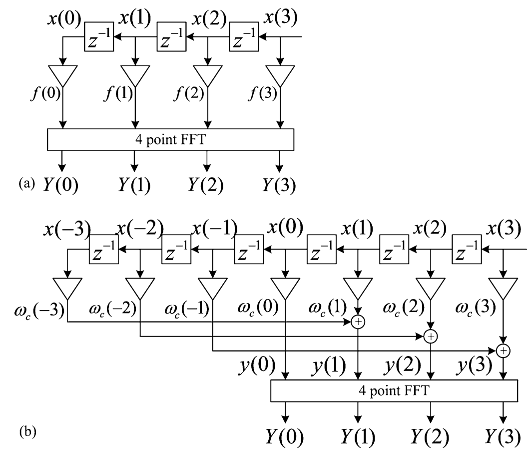

Fig. 1. Comparison of FFT and all phase FFT. (a) Procedures of FFT when $N=4$, f is N point window function. (b) Procedures of all phase FFT when $N=4$, ω_c is the convolution of two N points window functions.

c is the velocity of the laser beam, $d \ll L_0$, so $\gamma\mathrm{tr}(t)d$ is neglected. Then φ_F can be rewritten in the form of frequency and initial phase.

$$\varphi_F = 2\pi f t + \varphi \quad (8)$$

$$f = \frac{2\gamma\ \mathrm{tr}(t)}{ct}L_0 = \frac{2\gamma L_0}{c} \cdot \frac{d\ \mathrm{tr}(t)}{dt} \quad (9)$$

$$\varphi = \frac{4\pi\nu_0}{c}(L_0 + d) \quad (10)$$

Considering the expressions (2), (4), (8), (9) and (10), the frequency of the output power signal is unchanging with sawtooth current modulation and the moving information is included in the initial phase φ of output power.

Firstly, a reference phase φ_{ref} can be achieved if we apply all phase FFT, which will be particularly discussed later, to SMI signal when the external target is stopping ($d=0$). φ_{ref} corresponds to initial external cavity length L_0 with a difference of multiples of 2π. Then, when the target is moving, φ representing the actual position of the target (L_0+d) can be given, and a difference of multiples of 2π still exists. As φ is always limited to $\pm\pi$, a phase unwrapping procedure is essential to obtain the real phase φ_{true}. Unwrapping is processed due to the phase difference between two neighbouring phase. If the phase difference is larger than π or less than $-\pi$, 2π offset phase is added or subtracted from the preceding phase value repeatedly until the phase difference is less than π [18]. Then, the displacement d will be expressed as

$$d = \frac{c}{4\pi\nu_0}(\varphi_{true} - \varphi_{ref}) \quad (11)$$

2.2. All phase FFT for acquiring phase

All phase FFT, which improves the data truncating way and reduces the leakage greatly, is adopted to do phase estimation and then calculate displacement. All phase FFT has a pre-processing step before the conventional FFT. The equivalent pre-processing step can be summarized in Fig. 1. Comparing to FFT taking N samples, $2N-1$ samples are needed in all phase FFT. Multiplying the convolution of two N points window functions with $2N-1$ samples and then adding each two samples that have interval of N points together, N recombined samples is ready, then through conventional N points FFT, all phase FFT spectrum can be achieved [19].