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Phase extraction of non-stationary interference signal in frequency scanning interferometry using complex shifted Morlet wavelets

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ABSTRACT

Frequency scanning interferometry (FSI) with an external cavity diode laser is an effective technique for measuring the absolute distance of a target. However, because of the nonlinearity in optical frequency scanning, an interference signal becomes a non-stationary chirp signal, which is a critical issue to extract the phase of the interference signal for improving the accuracy of FSI. In this paper, a method for extracting the phase using complex shifted Morlet wavelet is proposed to accurately track the instantaneous phase of the chirp signal, and the selection of the wavelet parameters is also derived. The method is verified to be effective and stable by performing simulations and experiments. The experimental results demonstrate that the relative error of the phase extraction in the fractional part of interference signal is $< 1.5\%$;, and the standard deviation of absolute distance measurement is <1.69 μm

1. Introduction

With the properties of narrow line width, relatively broader mode free hopping tuning range and low cost, external cavity diode lasers (ECDLs) have found wider applications such as frequency scanning interferometry (FSI) for absolute distance measurement [1–3], coherent optical frequency domain reflectometry [4,5] and optical coherence tomography [6,7]. In these instruments, the ECDL plays an important role of providing a linear frequency tuning over a broad mode-hop-free frequency range [5,8]. However, there may have the mode-hopping phenomenon for some external cavity diode lasers (ECDLs) [9]. Since we use the ECDL having a broader mode free hopping tuning range in our FSI system, we could ignore this question. Because of the hysteresis and creep of the piezoelectric actuator (PZT) [4,10], the ECDL exhibits a nonlinear optical frequency scanning output, and therefore, the frequency of interference signal varies with time, which decreases the accuracy of extracting the phase of interference signal.

In general, an auxiliary interferometry is required to monitor the optical frequency output of the ECDL to suppress the nonlinearity of optical frequency scanning in real-time feedback control [11,12]. For example, Kakuma et al. [13] used an auxiliary interferometer with a fixed optical path to construct a phase-locked loop current feedback controller and adjust the laser current driving signal in real time to suppress the variations in the optical frequency scanning rate of the vertical-cavity surface-emitting laser diode. It is known that the nonlinear optical frequency tuning will result in the frequency spectrum peaks of interference signal during the Fourier transformation using data sampled at equal time intervals and degrade the spatial resolution of the interferometer. Another solution is to re-sample the measurement interference signal at equal sampling intervals in the frequency domain, in which the re-sampling time sequence is determined from the tuning optical frequency provided by an auxiliary interferometer [14]. Tae-Jung Ahn [15,16] applied an auxiliary interferometry with a fixed optical path to reconstruct the tuning optical frequency by the Hilbert transformation. On the basis of this, the measurement interference signal was resampled from equal frequency intervals by interpolations. As a result, the blurring phenomenon of the measurement interference signal frequency spectrum was significantly decreased, and the spatial resolution of the interferometer was improved. However, the spatial resolution is limited by the mode-hop-free tuning range of the optical frequency output of the tunable laser and the number of sampling points in an optical frequency scanning period. In our previous FSI system, Deng et al. [17] identified the transfer function of the ECDL laser system using state sub-space method and modelled the relationship between the optical frequency output and the PZT driving signal. The corrected PZT driving signal was then inversely generated from the inversed transfer function. Because the hysteresis and creep of the PZT depends on its driving signal frequency, a corresponding transfer function of the ECDL is required to be established for each PZT driving signal. However, there

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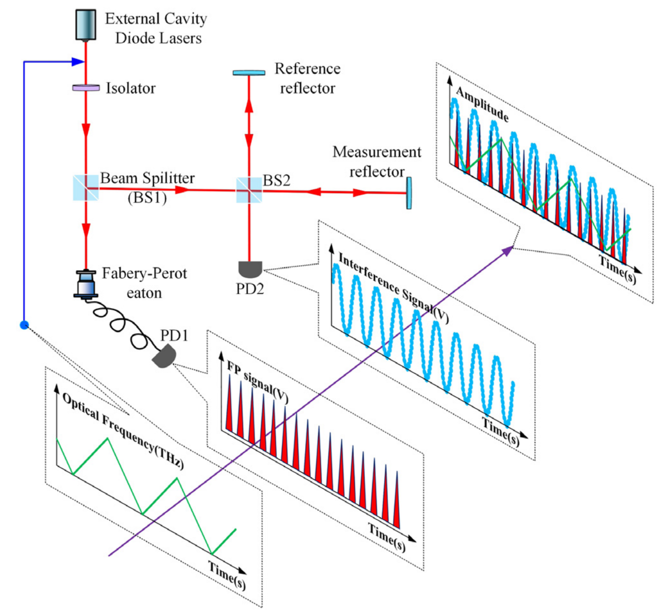

Fig. 1. Basic schematic setup of FSI.

will be different transfer functions because the laser outputs different optical frequencies under different conditions. Therefore, this method is suitable for the laser only under certain conditions.

More recently, to extract the instantaneous phase of the non-stationary signal directly, Liu et al. [18] proposed an extended Kalman filter (EKF) technique to track the instantaneous frequency (IF) of an interference signal, and therefore, the phase can be estimated by integrating the tracked IF over time. Because the method is independent of the laser source, it can eliminate the influence of nonlinear optical frequency scanning on phase extraction and greatly simplify the FSI system. In this method, assuming that the sampling rate of DAQ is much higher than the frequency of interference signal, three consecutive sampling points were used to approximately estimate the IF of inference signal, which is sensitive to the measurement noise of interference signal. However, it is vital for the EKF to choose the initial value, and it is difficult to choose a better initial value. In practice, the estimation of IF has been investigated in a significant number of applications, including machine condition monitoring [19,20], radars, communications and audio processing [21]. Among these methods, the complex continuous wavelet transform (CCWT) using complex shifted Morlet wavelets (CSMWs) [19,22] has showed a powerful ability to estimate the IF, instantaneous phase (IP) and instantaneous amplitude of a signal in the frequency domain because of its advantage of the simultaneous optimal selection of both the wavelet central frequency and the wavelet bandwidth.

In this paper, instead of estimating the IF of the interference signal, we use the CSMW to recover the fractional phase of non-stationary interference signal in FSI. The algorithm is tested on simulated non-stationary synthetic signals with different signal–noise-ratios (SNRs) and real interference signal of FSI. It was found that the proposed method for phase estimation presents a high accuracy of the recovered phase and is robust to noise.

2. Nonlinearity of optical frequency scanning in FSI

2.1. Principle of FSI

Fig. 1 shows the basic schematic setup of FSI. The FSI consists of a Michelson interferometer, an ECDL and F–P etalon. The ECDL is used as the light source, and its output beam is divided into two parts using a beam splitter (BS1). One beam enters the Michelson interferometer for absolute distance measurement, and an optical detector (PD2) is used to detect the intensity of interference signal. The other enters the F–P etalon for the measurement of the optical frequency scanning range of the ECDL by counting the resonance peaks with an optical detector (PD1). An arbitrary signal generator is used to drive the ECDL.

For a static target, the optical path difference (OPD) of Michelson interferometer is fixed. While scanning the optical frequency of ECDL over $\Delta\nu$, we can also get the interference signal, and by ignoring the DC component of the interference signal, the interference signal detected by PD2 can be described as follows:

$$x(t) = A\cos[2\pi f(t)t + \theta_0] \tag{1}$$

where A is the amplitude of the interference signal, $f(t)$ is the frequency and θ_0 is the initial phase of the interference signal.

The relationship between the IF of interference signal and the scanning rate of optical frequency of the ECDL is given as follows:

$$f(t) = \beta(t) \cdot \tau \tag{2}$$

where $\beta(t)$ is the scanning rate of optical frequency and τ is the time delay between measurement and reference arms.

Combining Eq. (1) with Eq. (2), the phase difference between any two points of the interference signal can be expressed as

$$\Delta\phi = 2\pi\tau\beta(t)(t_2 - t_1) = 2\pi\tau\Delta\nu \tag{3}$$

where $\Delta\nu$ is the scanning range of optical frequency of the ECDL.

Assuming that the length to be measured is L, the time delay τ can be described as follows:

$$\tau = \frac{2n_g \cdot L}{c} \tag{4}$$

where τ is the time delay, determined by the optical path difference between the two arms of FSI.

Therefore, the measured distance L can be obtained as follows:

$$L = \frac{c\Delta\phi}{4\pi n_g \Delta\nu} \tag{5}$$

where c is the speed of light in vacuum and n_g is the refractive index of air.

From Eq. (5), it is obvious that the accuracy of the measured length L depends on the corresponding measurement accuracy of $\Delta\nu$ and $\Delta\phi$. The relationships for $\Delta\nu$ and $\Delta\phi$ in time domain is shown in Fig. 2. The scanning range $\Delta\nu$ of optical frequency can be acquired by counting the resonance peaks, while the light beam passes through the F–P etalon, as shown in Eq. (6)

$$\Delta\nu = r \cdot FSR \tag{6}$$

where r is the number of the detected resonance peaks by PD1.

The corresponding phase $\Delta\phi$ of interference signal to $\Delta\nu$ can be expressed as follows:

$$\Delta\phi = 2\pi \cdot N_0 + \phi_f \tag{7}$$

where N_0 is the integer number of cycles of interference signal and ϕ_f is the fractional phase of interference signal and can be further written as follows:

$$\phi_f = \phi_{f1} + \phi_{f2}. \tag{8}$$

Because of the nonlinearity in scanning optical frequency of the ECDL, the interference signal is essentially a non-stationary signal. Obviously, the accuracy of fractional phase extraction has a considerable effect on the precision of interferometer.