Optics Communications 430 (2019) 234–237

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Do we need all the frequency components of a fringe signal to obtain position information in a vertical scanning wideband interferometer?

Dong Wei [a,*], Muzheng Xiao [b], Ping Yang [c]

[a] Department of Mechanical Engineering, Nagaoka University of Technology, Nagaoka City, Niigata 940-2188, Japan
[b] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, People's Republic of China
[c] Department of Mechanical and Electrical Engineering, School of Aerospace Engineering, Xiamen University, Xiamen City, Fujian Province, 361006, People's Republic of China

ARTICLE INFO

Keywords:
Instrumentation, measurement, and metrology
Fourier optics and signal processing
Interferometry
Metrology
Fringe analysis

ABSTRACT

Using a wideband light source based vertical scanning interferometer, we can obtain the position information of an object from the peak value of the envelope of the interference fringe signal. For the reconstruction of the envelope of this signal, it is necessary to select its frequency components; however, the question that naturally arises is whether there is a need to select all the frequency components of the signal to determine the position of the envelope peak. Based on our proposed method and subsequent optical experiments, we find that the peak position of the envelope can be estimated using only the frequency pairs that have high signal-to-noise ratios. Thus, this observation can be applied to not only improve the measurement performance of wideband scanning interferometers, but also to enable more complex and accurate optical metrology.

1. Introduction

As demonstrated by the white-light interferometer, the wideband light source-based vertical scanning interferometer plays an important role in shape measurement and distance ranging [1]. A femtosecond optical frequency comb (FOFC) [2] is an attractive wideband light source, because it offers the ability to measure a length not only in wavelength units, [3–5] but also in terms of adjacent pulse repetition interval lengths (APRILs) [6–11]. In particular, APRIL is inversely proportional to the repetition frequency of the FOFC laser measured based on the speed of light in vacuum. The speed of light in vacuum is used to define the unit of length "meter". Thus, by stabilizing the repetition frequency of the FOFC laser, the APRIL can also be stabilized. Because the APRIL can be derived using the definition of a meter, the comparability of the measured results can be ensured. Therefore, the APRIL can be used as a unit of length [12–14].

In the case of interference fringe signal processing, for demodulation, it is necessary to extract all the signal components in the frequency domain by using a frequency filter [15–19]. The working principle of the wideband interferometer is based on the concepts of signal processing and communication theories, especially signal modulation and demodulation [15]. In general, the reconstructed envelope based on all demodulated frequency components of the signals is used to identify the position information of the object. Naturally, a question arises: Do we need all the frequency components to obtain the position information of the envelope peak? This problem can be attributed to the fact that the model based on the communication theory does not agree with what needs to be obtained, which is the position of the peak of the envelope. We reproduce the signal components as they were before modulation, because, in the field of information communication, it is necessary to reproduce the transmitted signal without error. For signal processing, we need to obtain the peak position of the envelope; it is not necessary that the peak position must represent the envelope of the interference fringes for all frequency components.

Because we used a wideband light source in our study, the spectrum of the light source is distributed; in other words, the spectral intensity of each frequency component is different. However, we can suppose that the noise is uniformly distributed for each frequency; thus, the signal-to-noise ratio (SNR) of each frequency component is different. With this consideration, different envelopes can be reconstructed using all or part of the frequency components of the signal. Therefore, it seems natural to obtain the position of the peak of the envelope generated using only signals with high SNR. In general, a spectral signal with a high SNR has low noise; therefore, it follows that the higher the SNR is, the better the measurement accuracy will be.

In this study, a scheme utilizing pairs of frequency components to obtain the position of the envelope peak in a vertical scanning

* Corresponding author.
E-mail address: weidong@mech.nagaokaut.ac.jp (D. Wei).

https://doi.org/10.1016/j.optcom.2018.08.056
Received 2 July 2018; Received in revised form 16 August 2018; Accepted 21 August 2018
Available online 23 August 2018

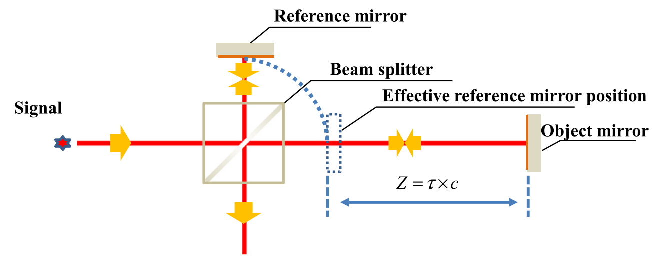

Fig. 1. Schematic diagram of a Michelson interferometer.

wideband interferometer was proposed. The remainder of the paper is organized as follows. In Section 2, first, the principles used for the determination of the envelope peak are introduced, and then the answer to the abovementioned question is presented. The proof-of-principle experiment conducted by us along with the experimental results are discussed in Section 3. Finally, the conclusions are presented in Section 4.

2. Principles

In our study, we consider a Michelson interferometer, which is depicted in Fig. 1. In the interferometer, light emitted from a light source is divided into two parts by a beam splitter cube; these two parts are then reflected by the object and reference mirrors, which then propagate onto a photo detector (PD), and are given by $u(t) = \int_{-\infty}^{\infty} S(\nu)\exp(-2\pi i\nu t)d\nu$ and $u(t+\tau) = \int_{-\infty}^{\infty} S(\nu')\exp\left[-2\pi i\nu'(t+\tau)\right]d\nu'$, respectively. Here, $S(\nu)$ represents the spectral distribution of the light source, while τ is the time delay of the reference arm relative to the object arm, which is determined by $\tau = \frac{Z}{c}$, where Z is the optical path difference (OPD) between the two arms and c is the speed of light in vacuum. The resultant intensity detected by the PD can be expressed as follows:

$$I(\tau) = \left\langle \left| u(t)/\sqrt{2} + u(t+\tau)/\sqrt{2} \right|^2 \right\rangle, \tag{1}$$

where $\langle\rangle$ represents a time-averaged operator. A calculated fringe pattern is shown in Fig. 2(a). The Fourier transform term of Eq. (1) can be further written as [18]:

$$\begin{aligned} \hat{I}(\nu) &= \mathrm{F}\left[I(\tau)\right] \\ &= I\delta(\nu) + \frac{1}{2}\left[|S(\nu)|^2 + |S(-\nu)|^2\right] \end{aligned} \tag{2}$$

where $\mathrm{F}(x)$ represents the Fourier transform of the variable x. In addition, $I\delta(\nu)$ describes the autocorrelation interference pattern of the reference and object beams, and $|S(\nu)|^2$ and $|S(-\nu)|^2$ describe the cross-correlation interference patterns that depend on the time delay between the two beams. Then, the Fourier transform is applied to the calculated fringe pattern; this is shown in Fig. 2(b). The $I\delta(\nu)$ and $|S(-\nu)|^2$ terms are not quantities of interest; therefore, they are eliminated using a frequency filter. The selected source spectrum $|S(\nu)|^2$ is the inverse Fourier transform onto the time domain. Then, the envelope function $|\gamma(t)|$ can be obtained as follows:

$$|\gamma(t)| = 2 \times \mathrm{F}^{-1}\left[\frac{1}{2}|S(\nu)|^2\right]. \tag{3}$$

Because the laser source owns a spectrum, the mth component of the Fourier transform can be expressed as follows:

$$S_m(\nu) = \left|S_m(\nu)\right| \exp(i \times \varphi_m). \tag{4}$$

The Fourier-transformed interferograms represent the relative strength $\left|S_m(\nu)\right|$ and interferometric phase φ_m as a function of the frequency component. The magnified version of the non-zero spectrum portion is shown in Fig. 2(b, inset). All the frequency components of the signals contribute to the formation of the envelope with different levels

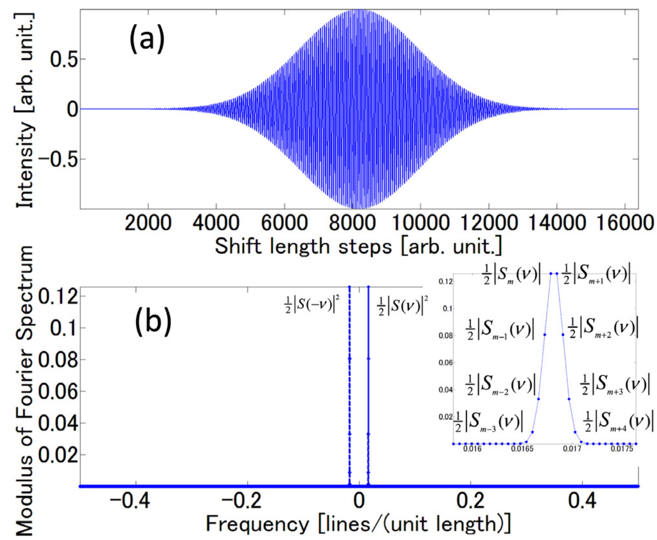

Fig. 2. Data processing for the wideband light interferometric measurement: (a) Interference fringe. (b) Spectrum of Fourier-transformed fringe pattern. (b, inset) Magnification of the non-zero spectrum portion.

proportional to the intensity of each signal. This can be expressed as follows:

$$|\gamma(t)| = \sum_m |\gamma_m(t)| = \sum_m \mathrm{F}^{-1}\left[\left|S_m(\nu)\right|^2\right]. \tag{5}$$

In our study, we consider whether we can determine the peak position of the envelope of the interference fringe by using the sinusoidal components (namely, a single or several $S_m(\nu)$) that were used to construct the fringe signal. It should be recalled that the peak position of the envelope of the interference fringes implies equal positions for the two mirrors, specifically, the position of the zero OPD [20,21]; this is the reason why we need to find the peak position of the envelope. Therefore, we focus on the statistical difference between the positions of the envelope peak, which are obtained using frequencies with different SNRs.

First, it should be noted that the strength of each $S_m(\nu)$ is different; therefore, the SNR of each $S_m(\nu)$ is different. In particular, the standard deviation of the envelope peak obtained using a spectral frequency component with a high SNR is small. Second, we need to consider the minimum number of frequency components required to obtain the envelope peak. Because one frequency component generates a cosine function with uniform amplitude, the peak of the envelope cannot be discriminated. In contrast, two frequencies constitute a frequency pair, which generates a beat signal. Therefore, it is possible to distinguish the peak of the envelope by using a frequency pair. Fig. 3 shows the reconstructed envelopes based on different frequency pairs. After the different frequency pairs of the spectra are selected, the selected spectra are then inverse Fourier-transformed. The absolute values of the inverse Fourier-transformed signals yield the envelope functions.

Theoretically, in the absence of noise, the central peaks of the different envelopes, which are reconstructed using different pairs of frequency components, match each other; this is evident from Fig. 3. However, in the case with noise, the SNR of the frequency pairs with high signal strength is good. Thus, the position of the envelope peak can be determined with high accuracy by using these frequency pairs with high SNR of interference fringes. Thus, in summary, we do not require all the frequency components for envelope peak determination. Therefore, our proposed method is more effective for practical use, because noise is a problem that cannot be avoided in actual experimental measurements. In the next section, we discuss our validation experiments.