Optics Communications 396 (2017) 216–220

Contents lists available at ScienceDirect

Optics Communications

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

3-D surface profile measurement using spectral interferometry based on continuous wavelet transform

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ARTICLE INFO

Keywords:
Interferometry
Wavelet transform
Surface profile measurement
Phase extraction
Signal processing

ABSTRACT

This study proposes a signal analysis technique that uses continuous wavelet transform for signal processing in a spectral domain optical coherence tomography system. Our method enables us to calculate the optical path difference simply by taking advantage of the fact that the product of the phase and wavelength becomes constant. Experimental results obtained using a pair of gauge blocks with a thickness difference of 40 µm confirm that the repetitive measurement accuracy was 65.1 nm. A demonstration of the three-dimensional surface profile measurement indicates that the rms measurement error is 0.17 µm.

1. Introduction

Optical coherence tomography (OCT) is an interferometric imaging technique based on low-coherence interferometry. OCT has been used in clinical applications [1], such as ophthalmoscopy [2], skin examination [3], and circulatory system examination [4], because it allows for noncontact and noninvasive measurements with high resolution and sensitivity. There are two main types of OCT: time domain OCT (TD-OCT) and Fourier domain OCT (FD-OCT) [5]. These OCT systems use a multi-wavelength light source to obtain depth information. The system resolution depends on the bandwidth of the wavelength of light. Therefore, a wide multi-wavelength light source is needed to achieve higher resolutions. Spectral domain OCT (SD-OCT), a type of FD-OCT, consists of a Michelson interferometer and a diffraction grating and image sensor for spectroscopy. The generated interference signal is spread linearly in space by the diffraction grating, and the sensor captures the spectrum of the interference signal. Thus, SD-OCT achieves higher sensitivity and speed compared to TD-OCT because the system does not require depth scanning; this technique is called spectral interferometry (SI) and is used for SD-OCT systems [6]. However, the phase of the interference signal varies nonlinearly because the phase is inversely proportional to the wavelength. Therefore, SD-OCT suffers from the problem that a temporally and spatially located interference signal will become a nonstationary signal, e.g., a chirp signal. A conventional Fourier transform (FT) is not suitable for processing a nonstationary signal because time or space information disappears. To process this signal, many techniques have been developed. One of them is the short-time FT (STFT), which has been widely used for frequency analysis [7,8]. STFT can identify variations in frequency by using a shifting window function. STFT analyzes a signal by using a particular window size; however, this window size is fixed for all frequencies. Therefore, accurate signal analysis is impossible in STFT if some nonlinearity remains in the viewing window. Another method is resampling of the wavenumber in the OCT signal prior to calculating the FT. This method converts the nonlinear wavenumber into a linear wavenumber [9]. However, the resampling method with a first order equation cause large interpolation error. Although other method uses custom prism to obtain linear wavenumber in spectrometer, complexity prism is required [10].

This study proposes a signal analysis technique in which continuous wavelet transform (CWT) [11] is used to obtain phase information corresponding to the wavelength.

CWT is a time-frequency analysis technique which detects the phase and instantaneous frequency simultaneously. It can be used to analyze a nonstationary signal by calculating the correlation with a mother wavelet with varying window size. The spatial variation of a signal is calculated as a wavelet coefficient that indicates the similarity between the mother wavelet and the signal. The instantaneous frequency of a nonstationary signal appears as a ridge in the wavelet coefficient, and phases are estimated from the maximum ridges of the wavelet coefficients [12–14].

Therefore, CWT need not the resampling in wavenumber for OCT signal and phase distribution can be obtained. As the variation in the wavelength of an interference signal is known by spectrometer, the

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http://dx.doi.org/10.1016/j.optcom.2017.03.053
Received 17 November 2016; Received in revised form 2 March 2017; Accepted 23 March 2017

optical path difference (OPD) can be easily calculated by multiplying the phase and the known wavelength. Although a similar two-wavelength method can also be used to calculate the OPD from the difference of phases obtained from the different wavelengths of the interference signals, it suffers from measurement errors when the detected phase is affected by noise. On the other hand, in CWT, the products of the phases and multiple wavelengths become linear when arranged in order of wavelength because the OPD is a constant value in an SD-OCT system. By using this feature, we can determine the measurement value of OPD using a linear approximation after obtaining a series of products. As a result, the measurement error in the OPD can be minimized compared with that of the two-wavelength method. We experimentally measured the OPD using an SI. We obtained the interference fringes of an object comprising a pair of gauge blocks with a thickness difference of 40 µm. Then, we applied a CWT to these fringes and calculated the two OPDs for the respective gauge blocks. The experimental result shows that the measurement repeatability is 65.1 nm. The result of the three-dimensional surface profile measurement confirms that the rms measurement error is 0.17 µm.

2. Principle

The relation between phase and wavelength is given by

$$a_i = 2\pi L/\lambda_i = \alpha_0 + \Delta\alpha_i\,(\mathrm{i} = 1, 2, \ldots \mathrm{m}), \tag{1}$$

where L, α_0 and Δa_i are an optical path difference (OPD), a phase offset and a phase distribution, respectively.

Fig. 1 shows an example of numerical calculation indicating phase vs wavelength and the product of phase and wavelength vs wavelength relations. From Eq. (1) we can see that if the wavelength changes linearly from 730 to 930 nm, as shown on the horizontal axis of Fig. 1 at an OPD of L=40 µm, the phase α_i varies nonlinearly, as shown in Fig. 1(a), because the phase of an interference signal is inversely proportional to its wavelength. Therefore, FT cannot calculate the OPD accurately because of this non linearity.

On the other hand, Eq. (1) also shows that 2πL is given by

$$2\pi\mathrm{L} = (\alpha_0 + \Delta\alpha_i)\lambda_i\,(\mathrm{i} = 1, 2, \ldots \mathrm{m}) \quad . \tag{2}$$

An OPD is accurately detected if phase offset α_0 and phase distribution $\Delta\alpha_i$ could be obtained. In this case, The OPD is given by the distribution of constant value as shown in Fig. 1(b).

To determine the phase distribution $\Delta\alpha_i$, we use a CWT for signal analysis instead of FT. A CWT analyzes a signal by measuring the correlation between the signal and the mother wavelet. The CWT of signal $f(x)$ is defined as

$$W(a, x) = (1/\sqrt{|a|})\int_{-\infty}^{+\infty} f(p)\psi(a, x)dp, \tag{3}$$

where $\psi(a, x)$ is a mother wavelet defined as

$$\psi(a, x) = \psi[(p-x)/a]. \tag{4}$$

$W(a,x)$ denotes the wavelet coefficient, p indicates the potion in space, and a and x are called scale and shift parameters, respectively. The scale a is the duration of the mother wavelet $\psi(a, x)$, and $1/a$ is proportional to its frequency. The shift parameter x indicates space information. Eqs. (3) and (4) show that the mother wavelet is transformed such that the similarity between the mother wavelet $\psi(a, x)$ and the signal $f(x)$ can be measured by changing the scale a and shift parameter x. If a is getting small, the mother wavelet $\psi(a, x)$ has high similarity to the high-frequency components of $f(x)$, and $W(a,x)$ is large for small a. These signal analysis are conducted using shift parameter x. The phase distribution $\Delta\alpha_i$ can be detected accurately by using a CWT.

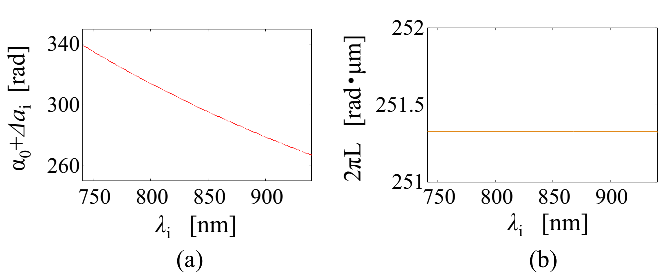

Fig. 1. Numerical calculation of (a) phase vs wavelength and (b) product of phase and wavelength vs wavelength relations.

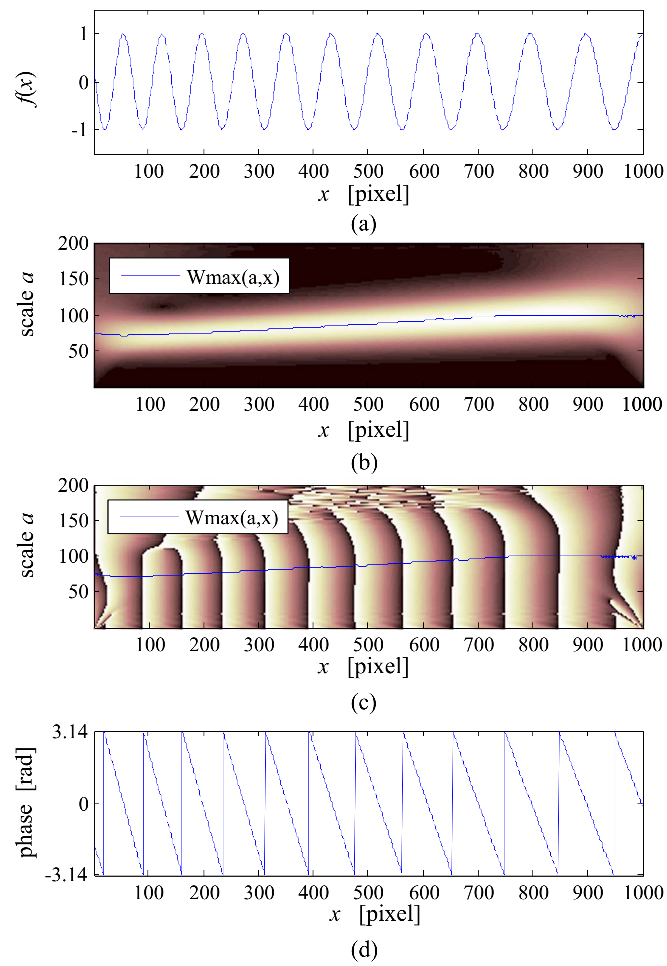

Fig. 2. Simulation results of the CWT: (a) chirp sinusoidal signal, (b) modulus map, (c) phase map, and (d) fractional phase.

We explain the signal process flow by using a mathematical software of MATLAB.

Fig. 2 shows the simulation results of the CWT. The test signal $f(x)$ is a chirp sinusoidal signal whose data number N is 1000, as shown in Fig. 2(a). Assuming that the interference signal is obtained by the detector, N is corresponded to number of pixel in a CCD camera. The phase extraction process is conducted with the following process; first, by using complex Morlet wavelet as a mother wavelet, CWT analysis is applied to the signal $f(x)$. The CWT results of the chirp signal $f(x)$ appears as a contour maps of $W(a,x)$ and the phase, respectively, as shown in Figs. 2(b) and 2(c). In this paper, these maps are referred to as the modulus map and phase map, respectively. The highest similarity in the signal $f(x)$ is represented as a maximum ridge of the wavelet coefficient $W(a,x)$ and it appears in modulus map. In Fig. 2(a), we can see that the frequency of test signal decreases gradually. In this case, scale a increases step by step.

Next, to determine the phase of the signal $f(x)$, we choose points located on the maximum ridges of the wavelet coefficients $W(a,x)$ for all x positions in modulus map. The coordinates of these selected points