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Discussion

Multi-frequency scanning interferometry using variable spatial spectral filter

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ABSTRACT

Recently, a variety of the optical comb-based interferometries has been developed for profilometry and tomography. However the interference amplitude and phase characteristics involving the center frequency and mode spacing of the optical comb have not been sufficiently studied. To investigate these multi-frequency interference characteristics, we proposed a broadband frequency variable quasi-comb generator utilizing 4-f optical system and a spatial spectral filter which can perform unrestricted scanning of the center frequency and mode spacing. By using a sinusoidal phase modulating interferometer with the quasi-comb generator, fundamental proof-of-principle experiments were successfully demonstrated. The interference phase fixation during the symmetrical varying of the mode spacing produced the interference amplitude peak envelope without fringes. On the other hand, it was confirmed that the interference phase was changed linearly without the amplitude change by the center frequency shift of the multi-frequency spectrum.

1. Introduction

Recently, the multi-frequency interferometries have been developed for high speed surface profile and tomographic measurement without mechanical scanning [1–4]. As typical techniques employed in the multi-frequency light source, the frequency combs lead to effective use of the repeated interference signals in a scanning direction (i.e. the high-order interference signals) such as white-light Fizeau-interferometer [5], non-mechanical fiber interferometer instead of a moving reference mirror [6], and scanless incoherent optical comb interferometry [7]. To develop 3-dimensional full-field measurement without mechanical components, the multi-gigahertz optical comb generator which enables to vary the frequency of the mode spacing and to provide a broad spectral bandwidth by employing a supercontinuum (SC) generation system with an optical pulse synthesizer has been proposed [8,9]. It is notable that the interferometric signal exhibits only peak envelopes without the interference fringe owing to the symmetrical varying of the mode spacing to the fixed center frequency. This leads to realizing of rapid measurements with less sampling points than those of conventional white-light interferometers.

Despite its potential advantages, it was revealed that the interference amplitude of the high order peak envelope changes depending on the interference phase determined by the center frequency and the optical path difference (OPD) of the interferometer [9]. It was also reported that spatial interference undulations depending on the value of the interference phase makes it difficult to provide a full-field surface profile measurement. To avoid these problems, two-wavelength compensation method using different interference signals from the other by a phase of $\pi/2$ was proposed [10]. This technique involved in the relation between the interference phase and amplitude is intimately related to the carrier envelope offset (CEO) phase [11–13] observed among the femtosecond optical pulse train of the frequency comb. The use of the CEO phase in the interferometry can lead to novel applications for the profilometer and tomography. From the view point of this demand, arbitrary varying of both the comb mode spacing and center frequency is critical factor, and the bandwidth should be broad enough to provide sufficient resolution for highly precise measurement.

As above, further study on the multi-frequency scanning interferometry is required to develop more practical applications. However, these interferometric characteristics have not been brought out definitely because conventional femtosecond lasers and monolithic comb generators including a cavity structure generally suffer from varying of the mode spacing and center frequency.

In this paper, we describe the principle of the interferometric characteristics in terms of the mode spacing and center frequency involved in the interference amplitude and phase. Furthermore, proof-of-principle experiments using a quasi-comb generator which employs a spatial spectral filter (SSF) in a Fourier transformation optical system is demonstrated. The proposed optical system enables to synthesize a variable and broadband multi-frequency

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spectrum using a super luminescent diode (SLD). The symmetrical mode spacing variation and the center frequency shift were conducted independently to exhibit the two effects of amplitude change without phase variation and the phase change without amplitude variation. In the experiments, the interference amplitude and phase values are obtained numerically by employing a sinusoidal phase modulating (SPM) interferometer [14].

2. Principle

2.1. Generation of the multi-frequency spectrum

The optical system which generates a quasi-comb spectrum for performing the multi-frequency scanning interferometry is shown in Fig. 1. The system consists of a 4-f optical system with diffraction gratings and a SLD as an initial light source. The first diffraction order light diffracted by DG1 forms a mapping of optical frequencies into spatial position along the horizontal axis x on the focal plane of a lens (L1). The formed spatial spectrum is a Fourier transformation of the incident light. The spectral mapping along the axis x follows a relation of

$$\nu(x) = \frac{c}{d(\sin\,\theta - (x/f))}, \tag{1}$$

where $\nu(x)$, θ, f and d are the mapped optical frequency, an incident angle to the grating, a focal length of L1 and the grating period of the DG1, respectively.

The SSF consisting of multiplicate transmissive slits introduced on the focal plane to select and transmit the intended frequency components directly. We define a center frequency ν_c as a frequency of a components passing through the Nth slit of which there are $2N+1$ slits in total. The transmitted multi-frequency components are recombined by L2 and DG2 to produce the quasi-comb spectrum expressed by

$$F(\nu) = G(\nu - \nu_c)[H(\nu) * \sum_{m=0}^{N} \delta\{\nu_c \pm m\Delta\nu)\}]$$
$$H(\nu) = \begin{cases} 1 & \text{for} \quad |\nu| \quad \leq \quad \frac{d\nu}{2} \\ 0 & \text{for} \quad |\nu| \quad > \quad \frac{d\nu}{2} \end{cases}, \tag{2}$$

where $\Delta\nu$, and $d\nu$ are the mode spacing, and the spectral line width of the multiplicate transmissive slits, respectively. δ and $*$ denote the Dirac delta function and the convolution operator, respectively. G and H denote the incident power spectrum of the SLD and an amplitude transmittance of one slit, respectively. The mode spacing $\Delta\nu$ is defined as

$$\Delta\nu \approx \frac{c}{f d \sin^2\theta}\Delta x, \tag{3}$$

where Δx is an interval length between the adjacent slits.

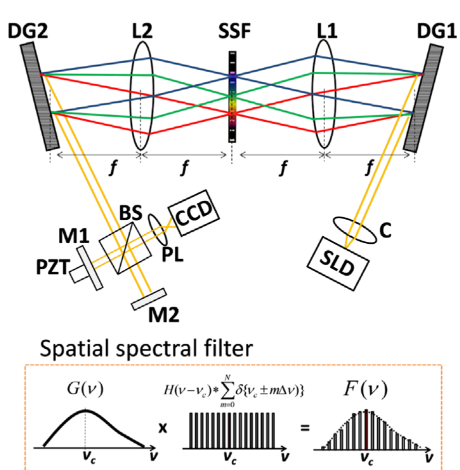

Fig. 1. Schematic of the multi-frequency interferometer with the quasi-comb generator. (SLD: super luminescent diode, C: collimator, DG1 and DG2: diffractive gratings, L1 and L2: focal lens, SSF: spatial spectral filter, BS: non-polarized beam splitter, M1: reference mirror, M2: sample mirror, PZT: piezoelectric transducer, PL: projection lens, and CCD: coupled charge device.).

2.2. Interferometric characteristics

According to the Wiener–Khinchin theorem, an interferometric signal of the multi-frequency spectrum can be obtained by real part of inverse Fourier transformation of Eq. (2). Thus, the interferometric signal as a function of an OPD L can be written

$$S(L) \propto h(L)\cos\left(2\pi\frac{\nu_c}{c}L\right)\sum_{n}^{\infty} g\left(L - n\frac{c}{\Delta\nu}\right), \tag{4}$$

where $h(L)$, and $g(L)$ denote the Fourier transformation of $H(\nu)$ and $G(\nu)$, respectively. It is well known that periodic high order peaks are continuously generated along the OPD of the interferometer [6,7]. Fig. 2 shows the principle of the multi-frequency interferometry in terms of the behavior of the high order interferometric peaks as a function of varied $\Delta\nu$ and L with a fixed value of ν_c.

Now, we consider the Pth order interferometric signal as a function of $\Delta\nu$ when the OPD is fixed at $L=L_p$. The interference term S_P can be written

$$S_P(\Delta\nu) \propto g\left(L_P - P\frac{c}{\Delta\nu}\right)\cos\left(2\pi\frac{\nu_c}{c}L_P\right). \tag{5}$$

During the symmetrical varying of $\Delta\nu$ around ν_c, S_P exhibits only amplitude envelope of $g(\Delta\nu)$ without the interference fringe, because the phase term $\cos(2\pi\nu_c L_P/c)$ is fixed. Fig. 2(c) shows the case of $P=1$. When $\Delta\nu=\Delta\nu_P=Pc/L_p$, S_P has a amplitude peak value of $g(0)\cos(2\pi P\nu_c/\Delta\nu_P)$. If the ratio of $\nu_c/\Delta\nu$ is exactly an integer, the phase becomes an integral multiple of 2π, which gives a maximum peak value of $g(0)$. In contrast, if the ratio of $\nu_c/\Delta\nu$ is a half-multiple integer, the phase becomes an integral multiple of π, which gives a negative peak value of $-g(0)$. As above, the ratio of $\nu_c/\Delta\nu$ plays an important role in the interference amplitude distribution influenced great deal by the interference phase. The phase value can be controlled independently by the shift of ν_c. In many case, the phase value at the interference amplitude peak position of higher order is shifted by $2\pi P\nu_c/\Delta\nu$ from 0 or 2π rad as shown in Fig. 2(d). This phase value can be changed freely if ν_c can be varied independently.

3. Experimental setup

The multi-frequency scanning interferometer with the proposed quasi-comb generator was constructed as shown in Fig. 1. The SLD with a center wavelength of approximately 860 nm was used as a light source. DG1 and DG2 are blazed gratings with 600 grooves/mm. The focus length of the L1 and L2 was 300 mm. The SSF with 17 slits of which the interval Δx is varied along to the y-axis was installed on the focal plane. The SSF was able to move vertically and horizontally by using a motorized stage with a stepping motor. The mode spacing in the SSF used in this experiment spreads out in a fan-like form as shown in Fig. 3. In accordance with the spectral mapping in Eqs. (1) and (3), $\Delta\nu$ and ν_c can be varied approximately linearly by mechanically moving of the SSF in the vertical direction (i.e. y-axis) and horizontal direction (i.e. x-axis), respectively. Ninth slit transmitted the center frequency component. The generated quasi-comb spectrum was observed by a spectral analyzer. The notable advantage of this optical system lies in to achieve a broadband comb spectrum more simply and at a lower cost than conventional femtosecond