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Suppression of subsidiary fringes in white light interferometry utilizing two-wavelength light source

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ABSTRACT

This paper analyzes and compares the two methods for suppressing the subsidiary fringes in white-light correlograms with two-wavelength light source. One of the methods adds the intensities of the two wavelength components and the other multiplies them. Peak intensity difference between the central fringe and the subsidiary fringes is investigated. A mathematical expression for a rapid estimation of the optimum wavelength difference between the two wavelengths is given for suppressing the subsidiary fringes. The effects of the intensities of the two wavelength components have also been investigated.

1. Introduction

White-light interferometric (WLI) sensors have been investigated by many researchers previously for a wide range of applications, which include thickness gauge [1], optical fiber sensor [2], surface profiler [3–6], and microscope [7]. One of the advantages of WLI sensors is that they can avoid the phase ambiguity by distinguishing the central fringe of the correlograms. Light-emitting diodes (LEDs) are energy efficient, light in weight, and low in cost comparing with conventional light sources. But the central fringe of a correlogram illuminated by a LED may not be easily distinguished by comparing the peak intensities of the interference fringes, especially when noise is present. K. G. Larkin has developed the efficient algorithms for the detection of the envelope of white-light correlograms [8], which may help to distinguish the central fringe. Two-wavelength methods can also be used to enhance the central fringe of the low coherence correlograms [9–13]. With a two-wavelength light source, a beat fringe pattern is generated in the correlogram and hence the subsidiary fringes are suppressed.

There are two types of two-wavelength methods. One of them is to add the intensities of the two wavelength components [9–13], and the other is to multiply them [12]. The fringe pattern produced by adding may be called added correlogram and that produced by multiplying as multiplied correlogram.

As shown in the upper part of Fig. 1, depending on the two wavelengths used, the second largest fringe in an added correlogram or a multiplied correlogram can either be the first subsidiary fringe or the largest fringe in the first subsidiary fringe packet. In order to suppress the subsidiary fringes, we will examine the normalized peak intensity difference between the central fringe and the first subsidiary fringe (NPID1), and the normalized peak intensity difference between the central fringe and the largest fringe in the first subsidiary fringe packet (NPID2). A mathematical expression will then be given for a rapid estimation of the optimum wavelength difference for suppressing the subsidiary fringes when the coherence length and the shorter wavelength are given. We will also look at the effects of the intensities of the wavelength components on the NPID1 and NPID2 of the correlograms.

This paper is divided into eight sections. Section 2 describes the added correlogram and the multiplied correlogram theoretically, and establishes a mathematical relationship between the two types of the correlograms. Section 3 compares the added correlogram and the multiplied correlogram, and analyzes the arithmetic difference between them. Section 4 derives expressions for NPID1 of the added correlogram and that of the multiplied correlogram. Section 5 derives expressions for NPID2 of the added correlogram and that of the multiplied correlogram. Section 6 gives an expression for the rapid estimation of the optimum wavelength difference for suppressing the subsidiary fringes. Section 7 looks at the effects of the intensities of the wavelength components on NPID1 and NPID2 of the correlograms when the intensity ratio of the two wavelength components varies from 0.1 to 10. Finally, Section 8 concludes the paper.

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2. Added correlogram and multiplied correlogram

When a Michelson interferometer is illuminated by a low coherence source, such as a LED, its output correlogram can be given by

$$I(x) = a\left\{1+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda}\right)\right\} \tag{1}$$

where a represents the amplitude of the central fringe of the correlogram, λ represents the central wavelength of the light source, x represents the optical path difference (OPD) of the interferometer, and l represents the coherence length of the light source.

When two low coherence sources of different colors are used to illuminate the Michelson interferometer, the correlograms of the two wavelength components can be expressed respectively as

$$I_1(x) = I_{01}\left\{1+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_1}\right)\right\} \tag{2a}$$

and

$$I_2(x) = I_{02}\left\{1+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_2}\right)\right\}, \tag{2b}$$

where λ_1 and λ_2 represent the central wavelengths, I_{01} and I_{02} represent the average intensities of the wavelength components.

By multiplying Eqs. (2a) and (2b), the multiplied correlogram can be written as

$$\begin{aligned} I_m(x) &= I_1(x)I_2(x) \\ &= I_0\left\{2+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_1}\right)\right. \\ &\quad \left.+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_2}\right)\right\} \\ &\quad -I_0\left\{1-\exp\left[-2\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_1}\right)\cos\left(\frac{2\pi x}{\lambda_2}\right)\right\} \\ &= I_a(x) - I_d(x), \end{aligned} \tag{3}$$

where $I_0 = I_{01}I_{02}$,

$$\begin{aligned} I_a(x) &= I_0\left\{2+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_1}\right)\right. \\ &\quad \left.+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_2}\right)\right\} \end{aligned}$$

represents the added correlogram, and

$$I_d(x) = I_0\left\{1-\exp\left[-2\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{2\pi x}{\lambda_1}\right)\cos\left(\frac{2\pi x}{\lambda_2}\right)\right\}$$

represents the arithmetic difference between the added correlogram and the multiplied correlogram.

The added correlogram can be rewritten as

$$I_a(x) = A\left\{1+\exp\left[-\left(\frac{x}{l}\right)^2\right]\cos\left(\frac{\pi x}{\lambda_m}\right)\cos\left(\frac{2\pi x}{\lambda_a}\right)\right\} \tag{4a}$$

and the arithmetic difference $I_d(x)$ can be rewritten as

$$I_d(x) = \frac{A}{4}\left\{2-\exp\left[-2\left(\frac{x}{l}\right)^2\right]\left[\cos\left(\frac{2\pi x}{\lambda_m}\right)+\cos\left(\frac{2\pi x}{\lambda_a/2}\right)\right]\right\}, \tag{4b}$$

where $A = 2I_{01}I_{02}$ is the amplitude of the central fringe of the added correlogram, $\lambda_a = 2\lambda_1\lambda_2/(\lambda_1+\lambda_2)$ is the average wavelength, and $\lambda_m = \lambda_1\lambda_2/|\lambda_1-\lambda_2|$ is the modulation wavelength. When the two wavelengths used are 0.78 μm and 0.67 μm, the average wavelength is about 0.72 μm and the modulation wavelength is about 4.75 μm.

It should be noted that Eq. (4a) represents the added correlograms when the intensities of the wavelength components are equal.

Eq. (4b) shows that the arithmetic difference consists of two oscillating terms. One of these oscillates at the modulation wavelength (λ_m) and the other oscillates at a half of the average wavelength ($\lambda_a/2$).

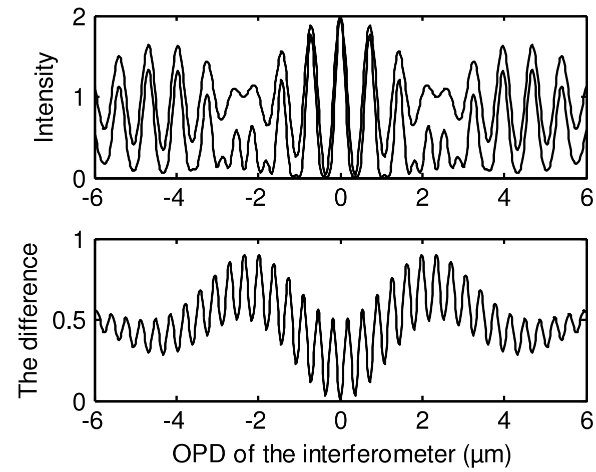

Fig. 1. The added correlogram I_a (upper graph in upper part), the multiplied correlogram I_m (lower graph in upper part), and the difference I_d (graph in lower part). Coherence length: 7.0 μm; two wavelengths: 0.78 μm and 0.67 μm.

3. Comparison between the added correlogram and the multiplied correlogram

Fig. 1 plots the added correlogram (given by Eq. (4a)), the multiplied correlogram (given by Eq. (3)), and the arithmetic difference between them, when the amplitude A is unity.

In the upper part of Fig. 1, the envelopes of the correlograms are modulated by the beat effect generated by the two wavelength components. The beat effect suppresses the subsidiary fringes.

In the upper part of Fig. 1, we also find the subsidiary fringes in the multiplied correlogram are smaller than those in the added correlogram.

There are two sinusoidal oscillations that can be seen in the graph in the lower part of Fig. 1. The faster oscillation has a wavelength of about 0.36 μm, which is a half of the average wavelength. The slower oscillation has a wavelength of about 4.7 μm, which is the same as the modulation wavelength. This is consistent with the theoretical result given by Eq. (4b) where the two oscillating terms are present.

From Fig. 1, it can also be seen that the central fringe of the arithmetic difference is about a quarter of the size of the central fringe in the added correlogram. This is consistent with the theoretical results given by Eqs. (4a) and (4b), where the number 4 can be seen in the denominator in Eq. (4b).

By examining the graph in the lower part of Fig. 1, the arithmetic difference has been maximized at the quadrature positions of the correlograms, and minimized when the correlograms reach the extreme values.

4. Estimation of NPID1

From Eqs. (3), (4a) and (4b), the peak intensity of the first subsidiary fringe of added correlogram can be given by

$$I_a(\lambda_a) = A\left[1+\exp\left[-\left(\frac{\lambda_a}{l}\right)^2\right]\cos\left(\frac{\pi\lambda_a}{\lambda_m}\right)\right], \tag{5a}$$

and the peak intensity of the first subsidiary fringe of multiplied correlogram can be estimated by

$$\begin{aligned} I_m(\lambda_a) &= A\left\{1+\exp\left[-\left(\frac{\lambda_a}{l}\right)^2\right]\cos\left(\frac{\pi\lambda_a}{\lambda_m}\right)\right\} \\ &\quad -\frac{A}{2}\left\{1-\exp\left[-2\left(\frac{\lambda_a}{l}\right)^2\right]\cos^2\left(\frac{\pi\lambda_a}{\lambda_m}\right)\right\}. \end{aligned} \tag{5b}$$