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Optimization methods of pulse-to-pulse alignment using femtosecond pulse laser based on temporal coherence function for practical distance measurement

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A B S T R A C T

An interferometer technique based on temporal coherence function of femtosecond pulses is demonstrated for practical distance measurement. Here, the pulse-to-pulse alignment is analyzed for large delay distance measurement. Firstly, a temporal coherence function model between two femtosecond pulses is developed in the time domain for the dispersive unbalanced Michelson interferometer. Then, according to this model, the fringes analysis and the envelope extraction process are discussed. Meanwhile, optimization methods of pulse-to-pulse alignment for practical long distance measurement are presented. The order of the curve fitting and the selection of points for envelope extraction are analyzed. Furthermore, an averaging method based on the symmetry of the coherence function is demonstrated. Finally, the performance of the proposed methods is evaluated in the absolute distance measurement of 20 μ m with path length difference of 9 m. The improvement of standard deviation in experimental results shows that these approaches have the potential for practical distance measurement.

1. Introduction

The invention of optical frequency comb has brought a profound revolution in the high-accuracy ranging, which provides many applications in the fields of science and technology, such as large-scale manufacturing and future space satellite missions [1–5]. In addition, the optical frequency comb can be referenced to a microwave-frequency clock, which can be directly transferred to the time standard with frequency stability better than 10^{-15} [6]. This outstanding characteristic enables the distance measurement using a femtosecond pulse laser to trace to the SI definition of the meter.

Since Minoshima and Matsumoto demonstrated a 240 m distance measurement using optical beat components of a femtosecond pulse laser in the year 2000 [7], various methods using femtosecond pulses for the distance measurement have been proposed. They can be roughly categorized into two groups. Some focus on the highly stabilized frequency of the comb. These approaches are presented in the radio-frequency wavelength interferometer [7,8], multi-wavelength interferometer [9–11], heterodyne interference interferometer [12], dispersive interferometer [13,14] and dual-comb heterodyne interferometer [15]. The others are based on the fine temporal characteristics of femtosecond pulses, and these methods combine incoherent time-of-flight (TOF) methods with temporal correlation detections, such as first-order coherence detection [16,17], second-order coherence detection [18,19] and balanced optical detection [20]. Because of the simple experimental system and high-contrast patterns, the first-order coherence detection is commonly used in the TOF distance measurement. Moreover, spectrum information of the light source could be acquired from the Fourier transformation of first-order coherence patterns according to the Wiener–Knintchine theorem. However, in such TOF distance measurement, the accuracy mainly depends on the process of the pulse-to-pulse alignment. In other words, the relative position of the overlapping pulses should be accurately obtained in the length measurement [21]. However, with the measured distance increases, the coherence patterns is chirped and broadened. Meanwhile, there are more turbulence and noise in the longer distance measurement. These factors influence the process of the pulse-to-pulse alignment, thus affect the final ranging results.

Recently, several attempts to measure distance have been made by observing the first-order temporal coherence patterns between different femtosecond pulses. In 2004, Ye firstly proposed an approach which provides both incoherent methods and coherent methods for absolute length measurement with an optical wavelength resolution [22]. In 2009, Wei et al. studied the temporal coherence function of the femtosecond pulse train from the comb, and the analysis of this theoretical model agrees with experimental results of a proof-of-the-principle experiment with optical path differences up to 6 m [23]. In the same year,

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Balling et al. established a numerical model of pulse propagation in air and compared different methods of interferograms detection. The relative agreement for short distance measurement is better than 10^{-7} in known laboratory conditions [24]. Meanwhile, Cui et al. experimentally demonstrated a distance measurement based on cross-correlation in a long distance, the measured distance is within 2 μ m at 50 m compared with a counting laser interferometer [25]. In 2010, Zeitouny et al. investigated correlation patterns in a dispersive unbalanced Michelson interferometer. A general model of cross-correlation functions is developed and compared to the results of measurements in air for path-lengths up to 200 m [26]. In 2013, Xu et al. discussed the effects of environmental parameters of refractive index in the air on the cross-correlation model [27]. In 2014, Wu et al. proposed an interferometric method by intensity detection in the dispersive and absorptive medium. The experimental results show that the maximum deviation is 45 nm in a range of 10 μm [28].

For practical long distance measurement, an unbalanced interferometer with a long measurement path and a short stable reference path could always be used. Due to the influence of unbalanced dispersive, the measurement pulse is chirped and broadened versus the reference pulse. In addition, in the pulse-to-pulse alignment process, disturbances from the long measured distance could bring more errors. Nevertheless, there are still no analyses for reducing these errors in the practical distance measurement. In order to resolve this problem, the temporal coherence function in the unbalanced dispersive Michelson interferometer must be known in advance. In this paper, the model of temporal coherence function is developed for long distance measurement based on Gaussian pulse model in the time domain, and this model is related to the group-velocity-dispersion (GVD) parameter of transmission medium and length of the measured path. Based on the simulation, the curve fitting in envelope extraction is also proposed to eliminate the influence of fringes shift in pulse-to-pulse alignment. Then, optimization methods of pulse-to-pulse alignment are firstly demonstrated to reduce the interference errors. They are caused by disturbances such as air turbulence, mechanical instability and electrical noise from the measuring instrument. Furthermore, an averaging method is proposed based on the symmetry of the coherence function. It has the potential for practical distance measurement for reducing the random error.

This paper is organized as follows. In Section 2, a numerical temporal coherence function is developed for the dispersive unbalanced Michelson interferometer. In Section 3, the interference fringes are discussed based on the established model, and the curve fitting in envelope extraction of the interferogram is presented. In Section 4, optimization methods of pulse-to-pulse alignment are proposed for practical long distance measurement. In Section 5, an averaging method is presented for reducing the random error in practical distance measurement. Then, the absolute distance measurement of 20 μm with path length difference around 9 m is described for experimental evaluation in Section 6. Finally, in Section 7, the conclusions are summarized.

2. Analysis of temporal coherence function for long distance measurement

In this section, we focus on the expression of temporal coherence function for the dispersive unbalanced interferometer with long measurement path in the time domain. The stable pulse train generated from a femtosecond frequency comb can be expressed as [23]:

$$E_{train}(t) = A(t)exp(i\omega_0 t + i(\varphi_0 + \Delta\varphi_{ce}t)) \otimes \sum_{m=-\infty}^{+\infty} \delta(t - mT_r) \tag{1}$$

where $E_{train}(t)$ is the electric field of a pulse train in the time domain. $A(t)$ is the pulse envelope, ω_0 is the central angular frequency and φ_0 is the initial phase of carrier pulse. In the frequency domain, the mode-locked femtosecond pulse laser is a comb with the repetition frequency f_{rep} and the offset frequency f_{ceo} from the initial frequency. In the time domain, the electric field packet repeats at the pulse repetition period $T_r = 1/f_{rep}$, and the carrier phase slips $\Delta\varphi_{ce} = 2\pi f_{ceo}/f_{rep}$ is caused by the difference between group velocity and phase velocity in the cavity [29]. Here, to simplify the analysis of temporal coherence function, we assume that the envelope of pulse is Gaussian pulse model, which can be expressed as $A(t) = \exp(-\Gamma t^2)$. Γ is the shape factor of Gaussian envelope, which is proportional to the inverse of the squared duration t_0.

In order to analyze the temporal coherence function of femtosecond pulses, a simple scheme based on a Michelson type interferometer is shown in Fig. 1. The pulse train from a femtosecond pulse laser is introduced into the interferometer, and it is split into two identical parts at the beam splitter (BS). The pulse train reflected from the reference mirror M_R and the relatively delayed pulse train from the target mirror M_T recombine at BS. The reference mirror and target mirror can be adjusted by a piezoelectric transducer (PZT). When the measurement pulse and the reference pulse overlap in space, the interference fringes can be observed on the oscilloscope.

In the unbalanced Michelson interferometer for long distance measurement, the length of measurement arm is much longer than the reference arm. To simplify this model, we ignore the length of the reference arm. Now, the electric field of the pulse reflected by the reference mirror can be expressed as

$$E(t,0) = \sqrt{\frac{\Gamma}{\pi}} exp(-\Gamma t^2 + i\omega_0 t + i\varphi_0) \tag{2}$$

The frequency Fourier transformation of $E(t, 0)$ is $E(\omega, 0)$. After the pulse propagated an optical path length x in the measurement arm, the model of pulse can be given as

$$E(\omega, x) = E(\omega, 0)exp(-ik(\omega)x) \tag{3}$$

where x is twice of the measured distance L in length, and $k(\omega)$ is a frequency-dependent propagation factor. In order to establish an analytical calculation of the propagation effects, the propagation factor is rewritten as a function of the angular frequency using the Taylor expansion. $k(\omega)$ can be expressed as following after applying the Taylor expansion

$$k(\omega) \approx k(\omega_0) + k'(\omega - \omega_0) + \frac{1}{2}k''(\omega - \omega_0)^2 \tag{4}$$

where

$$k' = \left[\frac{dk(\omega)}{d\omega}\right]_{\omega_0} \tag{5}$$

and

$$k'' = \left[\frac{d^2k(\omega)}{d\omega^2}\right]_{\omega_0} \tag{6}$$

where k'' is the GVD parameter which can be calculated from the empirical formulas such as the Ciddor equation [30]. The time evolution of the electric field of the pulse is derived from the calculation of the inverse Fourier transformation of Eq. (3), which is described in [31] and expressed as

$$E(t,x) = \sqrt{\frac{\Gamma(x)}{\pi}} exp\left\{-\Gamma(x)\left[t - \frac{x}{v_g}\right]^2 + i\omega_0(t - \frac{x}{v_\phi}) + i(\varphi_0 + N\Delta\varphi_{ce})\right\} \tag{7}$$

with

$$v_\phi = \left(\frac{\omega}{k}\right)_{\omega_0} = \frac{c}{n(\omega_0)} \tag{8}$$

$$v_g = \left(\frac{d\omega}{dk}\right)_{\omega_0} = \frac{v_\phi}{1 - \frac{\lambda}{n}\frac{dn}{d\lambda}} \tag{9}$$

$$\Gamma(x) = \frac{\Gamma}{1 + \xi^2 x^2} - \frac{i\Gamma\xi x}{1 + \xi^2 x^2} \tag{10}$$

where c is the speed of light in vacuum and equals to 299792458 m/s. $n(\omega_0)$ is the index of refraction. v_g and v_ϕ are group velocity and phase