Advanced optical metrology of geometrical quantity based on pulse trains’ destructive interference

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The interferometric measurement using the femtosecond optical frequency comb (FOFC) is in progress at present. We had analyzed the temporal coherence function of the FOFC since it is the fundamental description of interference phenomenon. As a result, it had been understood that the coherence peak exists during the time which is equal to the repetitions interval in the traveling direction of the FOFC. In order to make the best use of the temporal coherence characteristic, we propose a novel interferometric technique using an FOFC to observe the destructive interference between two pairs of pulse trains with different relative delays. Theoretical and simulation analysis of the FOFC shows that it offers a significantly different challenge for length measurement. This technique can be applied not only to surface profilometry and tomography, but also to optical super-high resolution metrology.

NOMENCLATURE

FOFC = femtosecond optical frequency comb
TCF = temporal coherence function

1. Introduction

Measurements of lengths are strongly demanded for not only science purposes but also industry requirements. Due to its increased frequency stability and very broad frequency band, the femtosecond optical frequency comb (FOFC) is a good choice for high precision long-distance measurements.

In 1998, Chekhovsky et al. suggested a possible scheme for a pulse distance-measuring interferometer using an FOFC as a low coherence light source. [1] In 2000, Minoshima and Matsumoto measured the phase shift of the FOFC beat component between longitudinal modes for long distance measurements. [2] In 2001, Yasui et al. proposed a method that high temporal coherence of an unbalanced optical-path Michelson interferometer produced an adjacent pair of pulse trains from an FOFC for length measurement to test stabilization of the FOFC light source. [3] Following that pioneering work, various experiments were proposed using the high temporal coherence peak between a pair of pulse trains for long measurements. In 2002, Yamaoka et al. reported a new interferometry technique by using high temporal coherence of different pair of pulse trains from an FOFC to precisely calibrate the group refractive index of air for improving length measurements. [4] In 2004, Ye proposed to use high temporal coherence between a different pair of pulse trains from an FOFC for a long arbitrary length measurement to be less than an optical fringe by changing the pulse repetition frequency of the FOFC. [5] In 2006, Ki-Nam Joo and Seung-Woo Kim reported a method that enables to measure the length between two consecutive pulse trains by observing the interference fringes in frequency domain. [6] In 2008, Cui et al. experimentally demonstrated a possible new scheme to apply the proposal of Ye, scanning the reference mirror of the unbalanced optical-path Michelson interferometer between the pulse repetition periods of the FOFC to obtain the interference fringes between different pairs of pulse train instead of changing the pulse repetition frequency of the FOFC. [7] In 2009, A numerical model of pulse propagation in air was reported and was applied to length measurements by using interference fringes between chirped pulses in short displacements by Balling et al. [8] and long displacements by Cui et al. [9].

Generally speaking, using only one FOFC light source for a length measurement to be less than an optical fringe that means one must to observe the interference fringes between pairs of pulse train. For a long arbitrary length measurement to be less than an optical fringe that means one must to observe the interference fringes between pairs of pulse train in the range of the pulse repetition periods of the FOFC as proposed by Ye to change the pulse repetition frequency of the FOFC and as proposed by Cui et al. to scan the reference mirror between the pulse repetition periods of the FOFC. However, it is a trade-off relation between the variability and the stability of frequency of the FOFC. And there is no simple device which can do scanning the range of the pulse repetition periods of the FOFC such as 30 cm [7] to 6 m [2] with sub-nanometer resolution.

Using two FOFC light source potentially provide another solution. But to obtain the intermode beat [10] or the interference fringes [11] between different pulse train from different FOFC light sources that means the following things of the two FOFC light sources. The very
good stability of phase locks and the differential frequency between the pulse repetition frequencies are required. The measurement system will become expensive and complicated.

However, to obtain the interference fringes between pairs of pulse train, the use of high temporal coherence in these experiments [1-9] is restricted to a pair of pulse trains. We have investigated the temporal coherence function of a pulse train from an FOFC. [12, 13] The results show that same high temporal coherence peaks exist during the period equal to the repetition intervals in the traveling direction of the FOFC. We have presented a novel interferometric technique using an FOFC to simultaneously observe “separated” high temporal coherence peak between two pairs of pulse trains with different relative delays [14-16]. As a special demonstration, measurement of the average temperature change over a distance of 3 m was also demonstrated. [14]

Based on these previous works, in this study, we demonstrated a modified Michelson interferometer to simultaneously observe “overlapped” high temporal coherence between different pairs of pulse trains from an FOFC for a long length measurement to less than an optical fringe. This is, to the best of our knowledge, the first demonstration of simultaneous observation of overlapped high temporal coherence peaks between two pairs of pulse trains with different relative delays. From a different perspective, our results show that this technique can be used as direct link between the FOFC and length measurement. Fortunately, this new approach to high-accuracy length metrology, by combining an ordinary Michelson interferometer and an unbalanced optical-path reversed-phase interferometer, has its own advantages. First, as shown below, this technique maintains the simplicity of the equipment. Second, the displacement metrology can be achieved without fringe analysis which typically restricted the measurement speed in an ordinary Michelson interferometer scheme. For simplicity of explanation, we have neglected the dispersion and absorption of the optical devices over the FOFC’s illumination bandwidth.

The outline of this report is as following: Section 2 gives a review of principles for the FOFC light source, the TCF of the FOFC and interference fringes’ formation between different pairs of pulse train, Section 3 investigates simulation, and lastly Section 4 presents a summary.

2. Principles

2.1 An FOFC

In the time domain, the “carrier” pulse moves with the center carrier frequency \( f_c \) of the FOFC. When the electric field packet repeats at the pulse repetition period \( T_r \), the “carrier” phase slips by \( \Delta \phi \) to the carrier-envelope phase because of the difference between the group and phase velocities. In the frequency domain, a mode-locked FOFC generates equidistant frequency comb lines with the pulse repetition frequency \( f_{rep} \propto 1/T_r \), and due to phase slip \( \Delta \phi \), the whole equidistant-frequency comb is shifted by \( f_{CEO} \).

2.2 TCF of an FOFC

For convenience of explanation, we herein briefly review and summarize the most important characteristic of the temporal coherence function of an FOFC, which can be founded in details in Ref.[12]

The power spectrum of an FOFC light source can be expressed as

\[
P(f) \propto A(f - f_c) \times \text{comb}(f_{rep}),
\]

where \( A(f - f_c) \) is the envelope function of the FOFC power spectrum. Based on the Wiener–Khintchine theorem, the interferometric signal of the autocorrelation function is given by the inverse Fourier transform of the spectrum of the source, and we have

\[
\gamma(\tau) \propto F^* \left[ A(f - f_c) \right] \otimes \text{comb}(T_r),
\]

\[
\text{comb}(T_r) = \sum_{m=-\infty}^{\infty} \delta(\tau - mT_r).
\]

From Eq. (2), the temporal coherence function periodically displays a high temporal coherence peak where the pulse trains signal of the FOFC displays a high-intensity peak with the pulse repetition period \( T_r \).

2.3 Interference fringes’ formation between two pairs of pulse train

The optical comb mode-lock technique results in interference fringes reappearing between different pairs of pulse trains. When one pulse train \( E_{\text{train}1} \) and the relatively delayed pulse train \( E_{\text{train}2} \) finally overlap in space, one can expect that interference fringes can be observed. After performing the time integration we obtain the interference fringes as

\[
I(t) \propto \left| \gamma(\tau) \right| \cos[\mod(h \times \Delta \phi, 2\pi)].
\]
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the surface of the mirror Mo1, and between the reference mirror MR and the surface of mirror Mo2, have the same value of amplitude and move in the same direction, but the slippage of the interference fringe phase to the carrier-envelope between them is reversed (namely, π). The result is that the two interference fringes completely cancel each other out when there is complete overlap (see Fig.3(b)). At the state of complete overlap, no interference fringes can be observed at the BS. In the case, that the two interference fringes partly overlapped each other, the amplitude of the obtained interference fringes will be reduced. (see Fig.3(a,c))

In essential, by observing the relative peak value of the acquired interference fringes, one can obtain the length information between two separated points.

3. Simulation

The simulation is carried out with a Gaussian profile polarization mode locked FOFC. The pulse duration, the repetition rate of the FOFC are 180 femtoseconds and 100 MHz, respectively. The output wavelength of the pulse is centered at λ=1550 nm with a spectral width of Δλ=80 nm. The corresponding coherence length is Lc = 26.5 μm.

Figure 4 illustrates the acquired interference fringes peaks formed for the surface of MR and Mo1, and the surface of MR and Mo2, respectively. As shown in Fig.4, we can confirm the interference fringe phase slip π to the carrier-envelope between acquired interference fringes.

As noted in Fig.5, the peak formed for the surfaces of MR and Mo1 comes close to the peak formed for the surface of MR and Mo2, by reducing the displacement between the two mirrors Mo1 and Mo2, the maximum peak value of the acquired interference fringes and the sum of the surface integral between the acquired interference fringes and the x axis are periodically reduced. When the two interference fringes peaks completely overlapped, by reducing the relative delay displacement between the two mirrors Mo1 and Mo2 equals to zero, the two interference fringes cancelled each other out. Then the acquired interference fringes value is zero.

4. Summary

We have presented a novel interferometric technique using an FOFC to observe the destructive interference between pairs of pulse trains with different relative delays for a length measurement. It is important to note that because it was possible to simultaneously observe “overlapped” high temporal coherence between different pairs of pulse trains with the reversed-phase, the relative positions of two separated point could be measured without fringe analysis. The results of this investigation show that, with an appropriate optical system, the FOFC can be used to observe the destructive interference for a length measurement. Finally, it is anticipated that the present technique will be a powerful metrological tool not only for surface profilometry and tomography but also for super-resolution metrology.

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Path difference [1 step= 26nm]

Normalized intensity [arb. unit]

Between \( M_R \) and \( M_{o1} \)

Between \( M_R \) and \( M_{o2} \)
REFERENCES


