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Remote Measurement Using a Femtosecond-Optical-Frequency-Comb-Based Interferometer

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Abstract: A novel interferometric technique using a femtosecond optical frequency comb (FOFC) is developed to measure the depth difference between two gauge blocks. The present technique is expected to be useful for remote measurement.

Keywords: Mode-locked lasers, Temporal Coherence, Interferometry, Remote measurement

1. INTRODUCTION

The increased frequency stability and the very-broad frequency band of femtosecond optical frequency comb (FOFC) has led to the application of this device in several precision metrology areas such as high-precision optical frequency metrology, spectroscopy, and distance measurements. We have investigated the temporal coherence function (TCF) of a pulse train from the FOFC [1]. The results show that high temporal coherence peaks exist during the period equal to the repetition intervals in the traveling direction of the FOFC. In the present study, we demonstrated an unbalanced optical-path Michelson interferometer for remote measurement by observation of high temporal coherence between different pairs of pulse trains from the FOFC. As a special demonstration, measurement of the depth difference of two gauge blocks with 3 m unbalanced optical path was demonstrated. For simplicity of explanation, we have neglected the dispersion and absorption of the optical elements over the FOFC's illumination bandwidth.

2. PRINCIPLES

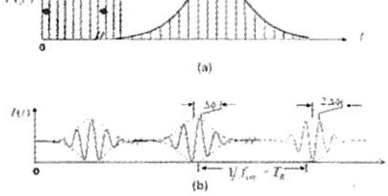

Fig. 1. Fourier-transform relationship between the power spectrum and the interference fringes. (a) Power spectrum of the FOFC. (b) Interference fringes; dotted line, the temporal coherence function of the FOFC; solid line: interference fringes.

In what follows, for convenience of explanation, let us first consider the temporal coherence function of the FOFC. The power spectrum of an FOFC light source can be expressed as:

$$P(f) \propto A(f-f_c) \times \sum_{m=-\infty}^{+\infty} \delta(f - mf_{rep} - f_{CEO}), \qquad (1)$$

where $A(f-f_c)$ is the envelope function of the FOFC power spectrum, f_c is the center carrier frequency of the FOFC. When the electric field packet repeats at the pulse repetition period T_R, the "carrier" phase slips by $\Delta\varphi_{ce}$ 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 $\Delta\varphi_{ce}$, the whole equidistant-frequency comb is shifted by f_{CEO}. Based on the Wiener–Khintchine theorem, the interferometric signal of the autocorrelation function is given by

$$\gamma(\tau) \propto \mathrm{F}^{-1}\left[A(f-f_c)\right] \otimes \sum_{m=-\infty}^{+\infty} \delta(\tau - mT_R). \qquad (2)$$

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.

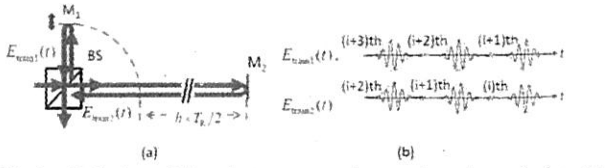

Fig.2. Relative delay between pulse trains formed by an unbalanced optical-path Michelson interferometer. (a) Simplified optical layout for interferometry. (b) Relative positions between two pulse trains (integer h=1).

Let us consider the interference fringes formed by an unbalanced optical-path Michelson interferometer, as shown in Fig. 2(a). First, the incoming pulse train is split into two identical parts. The mode-lock technique results in interference fringes reappearing at delays equal to hT_R. When the pulse trains $E_{\text{train}1}(t)$ and the relatively delayed pulse trains $E_{\text{train}2}(t)$ finally overlap at the BS (see Fig. 2(b)), one can expect that interference fringes can be observed, as shown in Fig. 1(b). After performing the time integration we obtain

$$I(t) \propto |\gamma(\tau)| \cos[\mathrm{mod}(h \times \Delta\varphi_{ce}, 2\pi)]. \tag{3}$$

3. EXPERIMENT

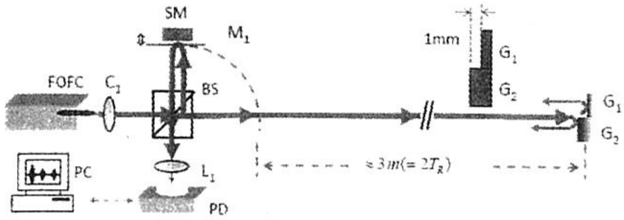

Fig. 3. Basic scheme for experiment. Abbreviations defined in text.

The basic scheme of the experiments is shown in Fig. 3. The experiment is carried out with a system consisting of an FOFC (FC1500, Menlo Systems, $f_{rep} = 100\,\text{MHz}$), an unbalanced optical-path Michelson interferometer, and system controls. The pulse trains from the FOFC is expanded and collimated by a collimator C$_1$ and introduced into the unbalanced optical-path Michelson interferometer. The unbalanced optical-path Michelson interferometer are composed of a beam splitter BS, a reference mirror M$_1$, and a combination object with two gauge blocks G$_1$ and G$_2$ with depth difference 1 mm. During the measurement, by moving the reference mirror M$_1$ of the interferometer by means of a computer-controlled and calibrated ultrasonic stepping motor SM, we could observe the interference fringes. After travelling different path lengths, these two pairs of pulse trains overlap at the BS. Lens L$_1$ images the interference fringes onto a photo detector PD.

Figure 4 illustrates the acquire interference fringes. The 1st and 2rd interference fringe signals exhibit a high contrast between the two pairs of pulse trains by the relative unbalanced optical displacement 2cT$_R$ (about 3 m, c is the light velocity in air.).

To obtain the relative average depth difference between two gauge blocks we analyzed the fringes pattern in Fig.4. Because the sampling theorem did not satisfy as noted in Fig.4, the Fourier transform method [1] was not able to be applied. The relative depth difference of two gauge blocks was measured as 939μm, a product of length corresponding to one scanning step and all the numbers of scanning steps between two peaks of fringes patterns. At a constant temperature, the fluctuations of displacement between two peaks of fringes patterns due to noise, such as mechanical vibration in the state, was measured as 2μm. The relative average depth difference of two gauge blocks was measured as 939±2μm. The experimental result is in agreement with the theoretical value within a standard deviation.

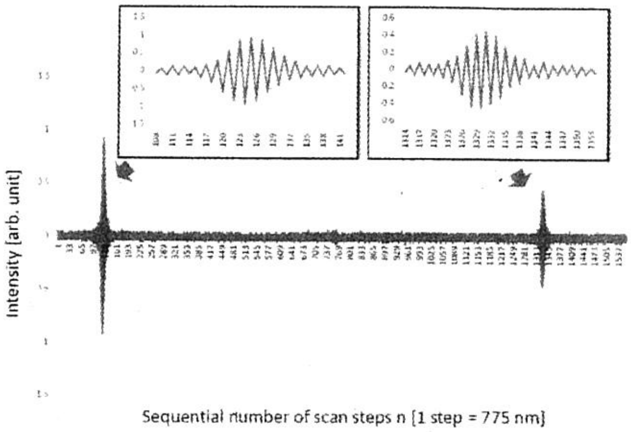

Fig. 4. Measured interference fringes.

4. SUMMARY AND FUTURE WORK

In summary, we have presented a novel interferometry technique using an FOFC to measure the depth difference of two gauge blocks with unbalanced optical-path about 3 m. The present technique is expected to be useful for not only surface profilometry but also tomography.

Note that in these experiments, the accuracy of the measurement is limited to the restricted resolution of the digital oscilloscope. We are currently pursuing an approach in which performance can be improved using an optical component with high accuracy and an appropriate design of the system, such as high-speed measurement.

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[1] Dong Wei, Satoru Takahashi, Kiyoshi Takamasu, and Hirokazu Matsumoto, "Analysis of the temporal coherence function of a femtosecond optical frequency comb," Opt. Express 17, 7011-7018 (2009)