Femtosecond Optical Frequency Comb for Volume Temperature Change Measurement

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Abstract: A novel interferometric technique using a femtosecond optical frequency comb (FOFC) is developed to observe the average temperature change over 3 m. The present technique is expected to be useful for environmental condition measurement.

Keywords: Ultrafast phenomena, Mode-locked lasers, Coherence, Interferometry, temperature measurement

1. INTRODUCTION

The increased frequency stability and the very broad frequency band of FOFC has led to the application of this device in several precision metrology areas such as precision optical frequency metrology, high-precision spectroscopy, and distance measurements. We have investigated the temporal coherence function (TCF) of a pulse train from 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 a modified Michelson interferometer to apply to environmental condition measurement by simultaneous observation of high temporal coherence between different paris of pulse trains from the FOFC. As a special demonstration, measurement of an average temperature change over 3 m 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

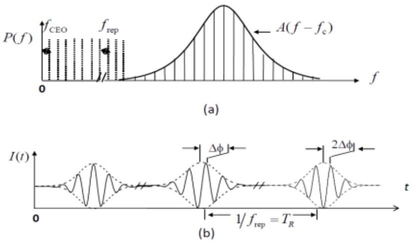

Fig. 1. Fourier-transform relationship between the power spectrum and the interference fringes. (a) Power spectrum of the FOFC. (b) Interference fringes; dotted line: the temporal coherence function of the FOFC; solid line: interference fringes.

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

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

where $A(f-f_{\mathrm{c}})$ 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 $\Delta\varphi_{\mathrm{ce}}$ 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 $f_{\mathrm{rep}} \propto 1/T_{\mathrm{R}}$, and due to phase slip $\Delta\varphi_{\mathrm{ce}}$, 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

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

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.

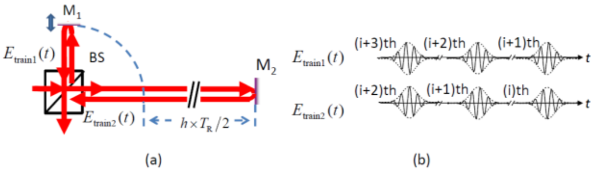

Fig.2. Relative delay between pulse trains formed by an unbalanced optical-path Michelson interferometer. (a) Simplified optical layout for interferometry. (b) Relative positions between two pulse trains (integer h=1).

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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

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

3. EXPERIMENT

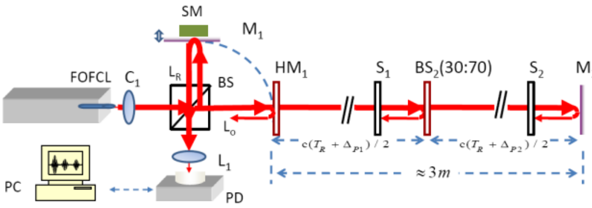

Fig. 3. Basic scheme for experiment. Abbreviations defined in text.

The basic scheme of the experiments is shown in Fig. 3. The experiment is carried out with a system consisting of an FOFC (FC1500, MenloSystems, $f_{\text{rep}} = 100\,\text{MHz}$), a modified Michelson interferometer, and system control. The pulse trains from the FOFC is expanded and collimated by a collimator C_1 and introduced into the modified Michelson interferometer. The modified Michelson interferometer is a combination of an ordinary Michelson interferometer and two unbalanced optical-path Michelson interferometer. The ordinary Michelson interferometer are composed of a beam splitter BS, a reference mirror M_1, and an object mirror HM_1. The unbalanced Michelson interferometer are composed of the same BS and M_1, and a different object mirror set BS_2 and M_2 to vary the relative delay between the three pulse trains, which are reflected by half-reflecting mirror HM_1, BS_2 and mirror M_2, respectively. During the measurement, by moving the common reference mirror M_1 of the three interferometers by means of a computer-controlled and calibrated ultrasonic stepping motor SM, we could observe the interference fringes. After travelling different path lengths, these three pairs of pulse trains overlap at the BS. Lens L_1 images the interference fringes onto a photo detector PD. The intensity of the interference fringes through the PD is measured with a digital oscilloscope and is sent to a computer PC.

Figure 4 illustrates the acquire interference fringes. The 2nd and 3rd interference fringes signals ,which appears when the shutter S_1 and S_2 are opened, exhibit a high contrast between the three pairs of pulse trains by the relative optical displacement $cT_R+c\Delta_{P1}$ (about 1.5 m, c is the light velocity in air.) and $2cT_R+c\Delta_{P1}+c\Delta_{P2}$ (about 3 m). The displacement $c\Delta_{P1}$ and $c\Delta_{P2}$ are introduced to avoid overlap each other between interference fringes in space.

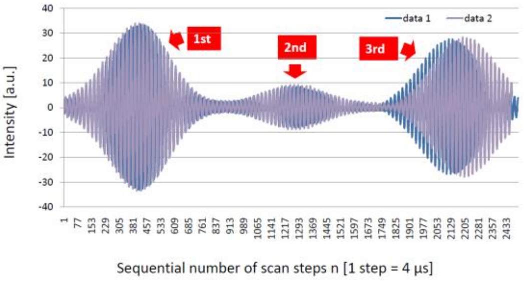

Fig. 4. Interference fringes were measured in the different temperatures.

As a special demonstration of environmental condition measurement, the proposal technique was applied to measure the average temperature change over an optical path of 3 m. As is known well, the amount of the change of the refractive index of air is about 0.9 ppm when the temperature of the surrounding air changes by 1 degree. Because of sensitivity to variations in temperature, when the temperature of the air between BS_2 and M_2 changes, the refractive index of air changes, and consequentially the relative optical path difference between BS_2 and M_2 changes. Data 1 , 2 and 3 were taken in the state of each temperature between BS_2 and M_2 t_1, $t_2(t_2 < t_1)$, and $t_3(t_3 < t_2$, and t_1-t_3 ≈ 0.2 ℃). As noted in Fig.5, as predicted, the 3rd peak goes away from the 1st peak when falling in temperature (the 1st peak is ovrelopped each other).

4. CONCLUSION

In summary, we have presented a novel interferometry technique using an FOFC to observe an average temperature change over 3 m. It is important to note that the measurement of the value such as air pressure etc. that influences the optical path difference is also possible with an appropriate optical system. The present technique is expected to be useful for environmental condition measurement and strain measurement of large equipment for social safety of the construction system.

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