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Absolute distance measurement using optical sampling by sweeping the repetition frequency

Bin Xue[a], Zhiyang Wang[a], Kai Zhang[a], Jianshuang Li[b], Hanzhong Wu[a,*]

[a] School of Marine Science and Technology, Tianjin University, Tianjin 300072, China
[b] National Institute of Metrology, Beijing 100013, China

A B S T R A C T

We experimentally demonstrate a method for long distance measurement using optical sampling by sweeping the repetition frequency of the frequency comb. The interferograms can be obtained by continuously changing the repetition frequency, and the distances can be determined via the peak position of the interferograms. Compared with the fringe counting interferometer, the experimental results show an agreement within ±3 μm in 75 m range.

1. Introduction

Frequency comb based absolute distance measurement has developed for a long period since the first realization by Minoshima in 2000 [1]. Various methods have been investigated in great depth both in the time domain and frequency domain [2], such as pulse cross-correlation [3–7], heterodyne interferometry [1,8], spectral interferometry [9–12], and dual-comb interferometry [13–15], etc. As length is of great importance in science and technology, technique of absolute distance measurement is still developing in a rapid pace, and attracting increasing interest all over the world [16,17].

Optical sampling is a powerful technique to perform time-resolved measurement with high frequency resolution and fast measuring speed [18,19], which has been widely used in many applications. In general, the time delay between the measurement and reference pulses (probe and pump pulses) can be adjusted with a mirror fixed on a mechanical translation stage, and the resulting signal can be detected and recorded by a low-speed photodetector and an oscilloscope. Nonetheless, the non-ambiguity range of distance measurement is strictly limited by the stroke of the mechanical range, e.g., 3 m stroke is needed to realize arbitrary distance measurement for the mode-locked lasers with 100 MHz repetition frequency. For such a long travelling path, the measurement speed can not be very high. Additionally, the variations of beam pointing and spot size can also make some contributions to the measurement uncertainty of the distance measurement.

Asynchronous optical sampling (ASOPS) is a novel technique, which employs two mode-locked lasers with a fixed repetition frequency differences [13–15,20]. The time delay between the measurement and reference pulses can be automatically scanned, and the scanning range can cover the total pulse period (the inverse of the repetition frequency) inherently, which means that there is no dead zone in the measurement path. Therefore, no mechanical stage is involved. The measurement speed is linked to the difference between the repetition frequencies, and ms-level (kHz-level difference) [13–15] and μs-level (MHz-level difference) [21–23] speeds for one single measurement have already been reported in the absolute distance measurement, showing powerful ability in the ultrafast science and applications. Please note that, the optimization of the repetition frequency difference is needed and useful [24], aiming to minimize the measurement uncertainty. The disadvantage of ASOPS is that two strictly synchronized mode-locked lasers are required, and the resulting system is bulky, expensive, and difficult to transfer.

Optical sampling by cavity tuning (OSCAT) has also attracted more attention recently [25,26]. Different from ASOPS, OSCAT relies on only one mode-locked laser, and thus the system is compact and easy to transport. The time delay between the measurement and reference pulses can be tuned by using a long fiber link and sweeping the repetition frequency. The non-ambiguity range is proportional to the sweeping range of the repetition frequency and the pulse index difference between the measurement and reference pulses (related to the length of the fiber link). Since the high frequency response of the piezoelectric transducer, the measurement speed can be at the same level as ASOPS. Mechanical scanning is still needed in the laser cavity, but much reduced scanning range can be enlarged significantly with much better mechanical stability. The drawback is that the long fiber link should be real-time stabilized with a feed-back loop, and the dispersion should be well compensated to generate high-quality interferograms.

Actually, optical sampling can be directly realized in the free space by sweeping the repetition frequency, which is more powerful in the space science and very large scale applications. In this case, only one mode-locked laser is needed, and hence the system is small-size and cost-efficient. In contrast to OSCAT, the long fiber link is not required any more. Consequently, the active stabilization of the long fiber and the dispersion compensation are not needed. The interferograms can be fast generated in a much more compact system, which can be used

* Corresponding author.
E-mail address: wuhz@tju.edu.cn (H. Wu).

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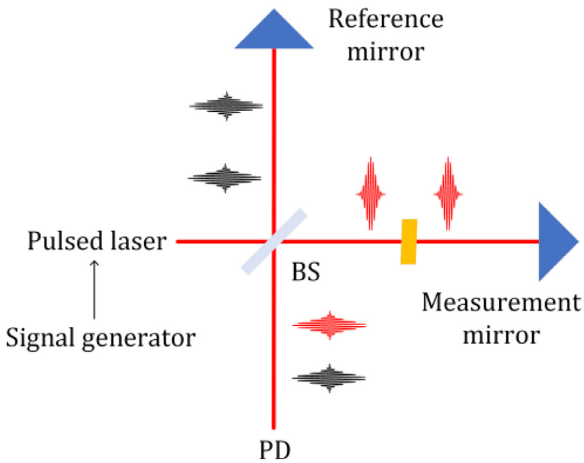

Fig. 1. Schematic of the experimental setup. BS: beam splitter; PD: photodetector.

to extract the distance information. In this paper, we theoretically and experimentally demonstrate long distance measurement using optical sampling by sweeping the repetition frequency (OSSRF). The principle is analyzed in detail, and the distance can be measured via the peak of the interferograms. Compared with the fringe counting interferometer, the experimental results show an agreement within ±3 μm in 75 m range.

2. Measurement principle

2.1. Optical sampling by sweeping the repetition frequency

Fig. 1 shows the schematic of the experimental setup. The pulsed laser emits a light pulse into a Michelson interferometer. The measurement pulse (reflected by the measurement mirror) and the reference pulse (reflected by the reference mirror) are combined at BS, and then detected by a photodetector. Since the unbalanced beam paths of the Michelson interferometer (as shown in Fig. 1, the measurement path is longer than the reference path), the temporal shift of the reference pulse differs from the measurement pulse when we change the repetition frequency of the laser source (described below). Therefore, the time delay between the measurement and reference pulses can be scanned with sweeping the repetition frequency, and the interferograms can be generated.

When we change the repetition frequency of the light source, the temporal shift d_1 of the measurement pulse can be given as:

$$d_1 = m_1 \cdot \frac{c}{n_g} \cdot \left(\frac{1}{f_{rep}} - \frac{1}{f_{rep} + \Delta f} \right) \tag{1}$$

where m_1 is the corresponding pulse index, c is the light speed in vacuum, n_g is the group refractive index of air, f_{rep} is the repetition frequency, and Δf is the variation of the repetition frequency. Similarly, the temporal shift d_2 of the reference pulse can be expressed as:

$$d_2 = m_2 \cdot \frac{c}{n_g} \cdot \left(\frac{1}{f_{rep}} - \frac{1}{f_{rep} + \Delta f} \right) \tag{2}$$

where m_2 is the corresponding pulse index. Therefore, the scanning range between the measurement and reference pulses can be calculated as:

$$d = (m_1 - m_2) \cdot \frac{c}{n_g} \cdot \left(\frac{1}{f_{rep}} - \frac{1}{f_{rep} + \Delta f} \right) \tag{3}$$

where, $m_1 > m_2$. Generally, Δf (several kHz, 10^{-5} relative to f_{rep}) is much less than f_{rep} (hundreds of MHz). Eq. (3) can be thus updated to:

$$d = m \cdot \frac{c}{n_g} \cdot \frac{\Delta f}{{f_{rep}}^2} \tag{4}$$

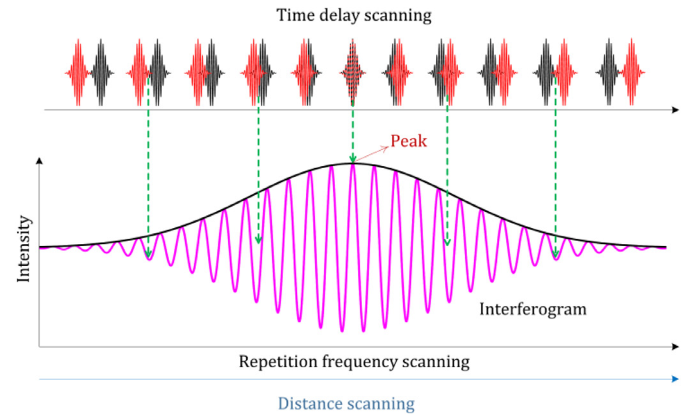

Fig. 2. Time delay scan between the measurement and reference pulse.

m can be given by

$$m = m_1 - m_2 = round\left(\frac{2L}{c/(n_g f_{rep})} \right) \tag{5}$$

In Eq. (5), L is the optical path difference between the measurement and reference beams. Based on Eqs. (4) and (5), we find that the scanning range d is proportional to m and Δf. A large optical path difference between the measurement and reference beams and a large tuning range of the repetition frequency can lead to a larger scanning range d. Fig. 2 shows the schematic of the time delay scan between the measurement and reference pulses, and the corresponding intensity detected by the photodetector.

In our previous work [27], we have analyzed the pulse cross-correlation function Γ of a femtosecond pulse laser, which can be expressed as:

$$\Gamma \propto \cos\left(\frac{2n_g(2\pi f_c)d}{c} + N \times \Delta\varphi_{ce} \right) \sum \int_{T_d} E^2(t)dt \tag{6}$$

In Eq. (6) f_c is the center frequency of the light source, and the air dispersion is neglected. d is the scanning range, as shown in Eq. (4), and is obtained by sweeping the repetition frequency. N is an integer. $\Delta\varphi_{ce}$ is the phase slip rate of the pulses due to the difference between the group velocity and the phase velocity. T_d is the integration time of the photodetector, and $E^2(t)$ is the envelope of the power density of the laser source. The distance can be measured when we successfully obtain the interferograms.

2.2. Absolute distance measurement using OSSRF

In the practical experiments, we sweep the repetition frequency by a triangle signal to avoid the mutation of the piezoelectric transducer. As shown in Fig. 2, the peak of the interferogram can be obtained by Hilbert transform (black solid line), which actually corresponds to the fractional part of the measured distance.

The distance L can be calculated by

$$L = \frac{1}{2} \cdot \left(m \cdot \frac{c}{n_g} \cdot \frac{1}{f_{rep}} - l_1 \right) = \frac{1}{2} \cdot \left(m \cdot \frac{c}{n_g} \cdot \frac{1}{f_{rep} + \Delta f} + l_2 \right) \tag{7}$$

where l_1 is the fractional part when we increase the repetition frequency, and l_2 is the fractional part when the repetition frequency is at the decreased period, which is shown in Fig. 3. d is the scanning range, and can be determined with parameters of m, Δf, and f_{rep}. Consequently, l_1 and l_2 can be easily measured. We find that d equals to $l_1 + l_2$.

3. Experimental setup

Fig. 4 shows the experimental setup for absolute distance measurement. The measurement system is composed of two parts: the main inter-