

# ABSOLUTE DISTANCE MEASUREMENT IN AIR USING DUAL FEMTOSECOND LASERS

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## Abstract:

A dual-comb-based distance measurement method is proposed, which can measure the optical distance of the fundamental and the second harmonics simultaneously, so that two-color method can be applied to correct the refractive index of air. In a 1.6 m long distance measurement, the stability is about 10  $\mu\text{m}$ . In the step-by-step linear test with a range of 1.2 m, the measurement accuracy is demonstrated to be about 20  $\mu\text{m}$ . The results show the present method can be applied in practical distance measurement.

## Keywords:

Dual frequency comb, distance measurement, the refractive index of air

## 1. INTRODUCTION

An optical frequency comb emits an evenly spaced ultra-short pulse train with a broad spectrum consisting of discrete, uniform mode-spacing narrow lines. It can become an ultra-stable ruler in the space, time and frequency domains when its mode frequencies are referenced to a frequency standard [1]. Such inherent advantages are attractive for absolute distance measurement. Since the pioneering work undertaken by Minoshima et al. [2], various methods have been reported for such studies [3-9]. Especially, the dual-comb method has been demonstrated to be able to realize large dynamic range measurements of absolute distance with high precision or resolution at high speed [6]. Subsequently, more groups modified and extended this method for distance measurement [10-12]. However, if this method is applied for practical measurement in air, the accuracy will be mainly depended on the uncertainty in the refractive index of air. Therefore, it is necessary to develop a correction method of the refractive index of air for the dual-comb system.

The refractive index of air is sensitive to the environmental parameters such as the air temperature, pressure, humidity, and CO<sub>2</sub> concentration, e.g., either a fluctuation of 0.1 K in air temperature or 0.4 hPa in air pressure will cause a fluctuation of  $1 \times 10^{-7}$  in the refractive index of air. Traditionally, empirical equations [13,14] are widely used for estimating the refractive index of air based on precise measurements of environmental parameters. However, because of the air turbulence or non-uniformity of

environmental conditions in practical distance measurement, it is very difficult to get the accurate distribution of these parameters along the optical path.

In our previous study, we have demonstrated the two-color method based on optical frequency comb is able to realize high-accuracy correction of the refractive index of air without precise knowledge of the environmental parameters [15,16], but it has not been applied in practical distance measurement yet. In this study, we present a dual-comb based distance measurement system that can realize two-color correction of the refractive index of air, and apply it in absolute distance measurement.

## 2. MATERIALS AND METHODS

### 2.1 Experimental setup

Two mode-locked Er:fiber ring lasers (FLFC<sub>1</sub> and FLFC<sub>2</sub>) with slight difference in repetition frequency ( $f_{\text{rep}}$ ) were used as the frequency comb sources (Fig. 1). The repetition frequencies of the two lasers were stabilized and referenced to a Rubidium clock. The pulses from FLFC<sub>1</sub> ( $f_{\text{rep}} = 56.171$  MHz) are introduced into second harmonic generation optics (SHG<sub>1</sub>) for second harmonic (SH) generation, then the unconverted fundamental ( $\nu$ ) and the SH ( $2\nu$ ) are coaxially introduced into an unbalanced Michelson interferometer. The pulses out of the interferometer are mixed with the fundamental and SH pulses from FLFC<sub>2</sub> ( $f_{\text{rep}} = 56.1685$  MHz) at BS<sub>2</sub>. Then the fundamental and SH pulses are separated by a dichroic mirror (DM), and detected by two photodetectors (PD<sub>1</sub> and PD<sub>2</sub>, respectively). Before the two photodetectors, two bandpass filters (BPF<sub>1</sub>: 1560 nm, FWHM 2 nm, BPF<sub>2</sub>: 780 nm, FWHM 1 nm) are used to limit the transmitted optical bandwidth to improve the optical sampling [6].

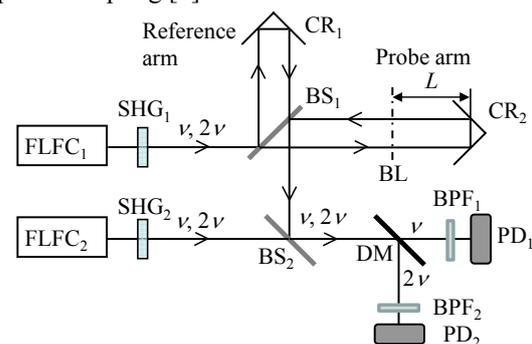


Fig. 1: Schematic of experimental setup. FLFC<sub>1,2</sub>: Femtosecond laser frequency comb; SHG<sub>1,2</sub>: Second harmonic generation optics; BS<sub>1,2</sub>: Beam splitter; BL: Base line; CR<sub>1,2</sub>: Corner reflector; DM: Dichroic mirror; BPF<sub>1,2</sub>: Band pass filter; PD<sub>1,2</sub>: Photodetector.

## 2.2 Processing

Due to the slight difference of the repetition frequency between the two lasers, the pulses from FLFC<sub>2</sub> will overlap with the pulses from the reference arm and probe arm of the interferometer periodically. We called FLFC<sub>1</sub> the signal laser (SL) and FLFC<sub>2</sub> the local oscillator laser (LO). In each LO repetition period, there is a slip time between pulses from two lasers as

$$\Delta Tr = \frac{fr\_LO - fr\_S}{fr\_LO \cdot fr\_S} \quad (1)$$

In the period

$$T_{update} = \frac{1}{fr\_LO \cdot fr\_S \cdot \Delta Tr} = \frac{1}{fr\_LO - fr\_S} \quad (2)$$

two pulses will overlap, separate and overlap again, which reflects to the measuring speed.

The time-of-flight information was derived from the two interferograms to calculate the target distance  $D$ . By using FFT analysis, the relative phase between the two interferograms fits the formula

$$\frac{d\phi(\nu)}{d(\nu)} = \frac{D_0 c}{4\pi} \quad (3)$$

where  $D_0$  is the optical distance which equals the target distance  $D$  multiplies the air refractive index,  $c$  is the speed of light and  $\nu$  is the optical frequency. By linear fitting the relative phase with the corresponding frequency, the slope  $k$  is obtained. Then the optical distance  $D_0$  can be determined by

$$D_0 = \frac{k \cdot 4\pi}{c} \quad (4)$$

In the distance measurement, the optical distance corresponding to the fundamental and SH can be obtained simultaneously, and denoted as  $D_1$  and  $D_2$ , respectively. Denote the group air refractive indices of the fundamental and SH as  $n_{g1}$  and  $n_{g2}$ ,  $D_1$  and  $D_2$  can be expressed as  $D_1 = n_{g1}D$  and  $D_2 = n_{g2}D$ . By applying the two-color method, the target distance  $D$  can be determined [2, 15, 16]

$$D = D_1 - A(D_2 - D_1), \quad (5)$$

where  $A$  is a coefficient defined as

$$A = (n_{g1} - 1) / (n_{g2} - n_{g1}). \quad (6)$$

Coefficient  $A$  is normally considered as a constant that can be easily determined based on rough measurement of the environmental parameters.

## 3. EXPERIMENTS AND RESULTS

To evaluate the present system, we first test its repeatability in distance measurement. The target mirror was placed at a distance around 1.63 m and kept stationary. We used the present system to measure the distance for 16 times. In each measurement, the data was recorded for 0.5 s for time averaging. The time interval between the measurements is nearly 30 s. Because the target mirror was kept stationary, so the target distance  $D$  obtained in this test should keep

stable. It was observed as a constant with a standard deviation (S.D.) of 10  $\mu\text{m}$  (Fig. 2). The instability of  $D$  is mainly caused by the instability of  $(D_2 - D_1)$ , which was amplified by  $A=47.2$ . In this test, the S.D. of  $(D_2 - D_1)$  is 0.21  $\mu\text{m}$ . The stabilities of  $D_1$  and  $D_2$  were also tested, which show S.D. of 0.77  $\mu\text{m}$  and 0.86  $\mu\text{m}$ , respectively (Fig. 2).

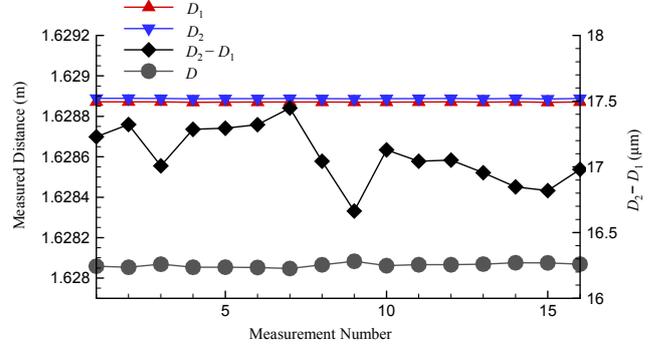


Fig. 2: Repeatability test of the distance measurement.

To further evaluate the present distance measurement method, the target mirror was moved by twelve steps at an increment of 100 mm. The displacements of the target mirror were measured by a commercial heterodyne interferometer for a comparison with the distance measured by the present system. They are in good accordance [Fig. 3 (a)]. By application of linear fitting, the slope is 1.00000, and the correlation coefficient ( $R^2$ ) is 1.00000. The residuals range from  $-19$  to  $23\mu\text{m}$  [Fig. 3(b)].

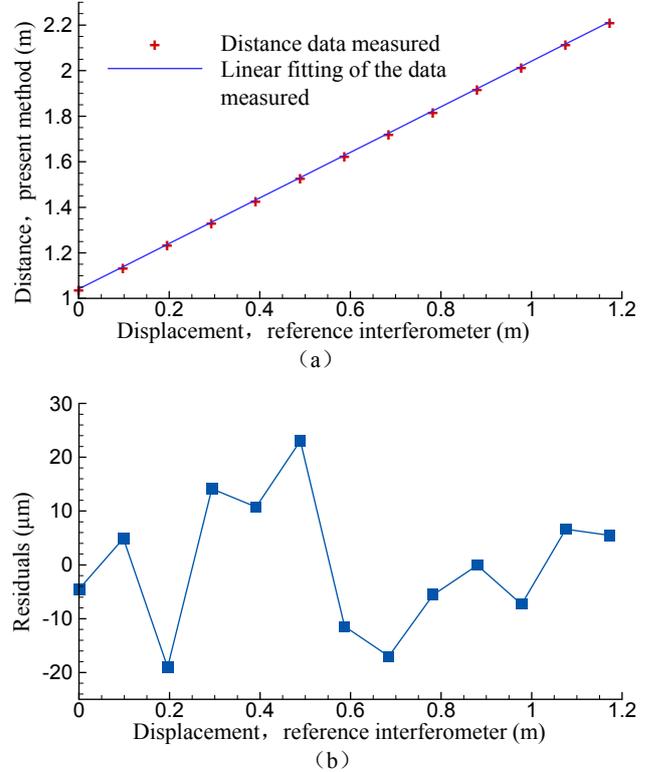


Fig.3: Linear test of the distance measurement. (a) The data measured by present method versus the data obtained by the commercial interferometer. (b) Residuals in the data comparison.

The above results show the present method can correct the refractive index of air efficiently and realize high accuracy distance measurement in practical case. The main error source is resulted from the measurement of  $(D_2 - D_1)$ . Our following research will be focused on improving the accuracy of  $(D_2 - D_1)$ .

#### 4. CONCLUSION

In conclusion, we proposed a dual-comb-based distance measurement method that can measure the optical distance of the fundamental and the second harmonics simultaneously, so that two-color method can be applied to correct the refractive index of air. In a 1.6 m long distance measurement, the stability is about 10  $\mu\text{m}$ . In the step-by-step linear test with a range of 1.2 m, the measurement accuracy is demonstrated to be about 20  $\mu\text{m}$ . The results show the present method can be applied in practical distance measurement.

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