Super-heterodyne Interferomter for Length-Measurment Using the Beat Signal of Laser Diodes and the Optical Frequency Comb

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Abstract

We proposed a super-heterodyne interference system for absolute length measurements using multiple laser diodes and an optical frequency comb as the light sources. The frequencies of the laser diodes will be phase-locked on the different modes of the optical comb with different offset frequencies for the method of excess fractions. The measurement range can be changed when frequencies of the laser diodes are phase locked on different modes of the optical comb, and the step-by-step measurement can be realized. The preliminary experiments were done to compare the measurement stability of two optical combs and a laser diode using a heterodyne interference system. The result shows that the measurement stabilities in 50 s of optical comb and laser diode were similar. The measurement standard deviation decreases to several tens of nanometres when the time constant of lock-in amplifier increases to 10 s.

1 Principle

The optical frequency comb is considered as the laser source or the frequency standard in various interferometers proposed to realize long-distance measurement because of its high frequency-stability and high accuracy, which is traceable to the definition of second. The frequency f of any mode within an optical comb can be expressed as $f = Nf_r + f_{ceo}$, where f_r is the repetition rate, f_{ceo} is the carrier envelop offset frequency and N is an integer. The uncertainty of f_r can be traced with high precision to the frequency standard in use, so if the frequencies of several continuous-wave laser diodes (cw LD) are locked on the different modes of a stabilized optical comb, the frequency separations among them will have the same stability and accuracy with f_r.

Figure 1 shows the schematic of the super-heterodyne interference system for length measurement based on two laser diodes and an optical comb. The laser diodes are the probe lights, the optical comb is the reference light, and the multiple-wavelength method is used. When two laser diodes f_1 and f_3 are locked on the modes of the optical comb with the offset frequencies of Δ_1 and Δ_3, the beat signal of laser diodes and the optical comb will be (Δ_3 -Δ_1), which is several tens of kilohertz.

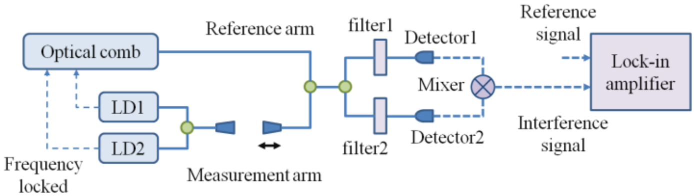

Figure 1: the schematic of the super-heterodyne interference system.

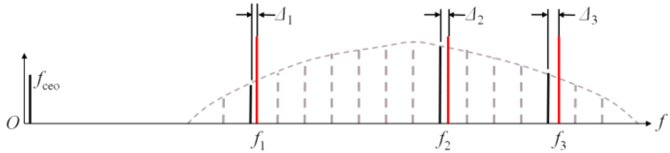

Figure 2: frequencies of laser diodes locked on an optical comb with different frequency offsets.

The synthetic wavelength can be changed by using different modes of the optical comb, and the measurement range is changed. When the value of (f_3 -f_1) is 1 THz, the synthetic wavelength is about 300 μm, and the measurement resolution is micrometres; the value of (f_3 –f_2) is several gigahertzes, the synthetic wavelength will be tens of millimetres, and the resolution will be hundreds of micrometres. Therefore, the step-by-step measurement can be realized, and finally, the conventional measurement using one laser diode is realized with a high accuracy of several nanometres.

2 Preliminary experiment and results

2.1 Experimental setup

The preliminary experiment to compare the measurement stability of optical combs (Comb1 and Comb2) and a cw LD has been done for measuring the distances of 22.478 m and 22.909 m. Comb1 (f_r = 100.0000 MHz) is stabilized to a Rb frequency standard and the stability is10^{-10} order. Comb 2 (f_r = 58.9286 MHz) is stabilized to a GPS frequency standard. The center wavelengths of the two optical combs are the same as the wavelength of the LD.

Figure 3 shows the schematic of the heterodyne interference system used for the experiment, which is based on an unbalanced optical-path Michelson interferometer. A switch is used to select the light sources.

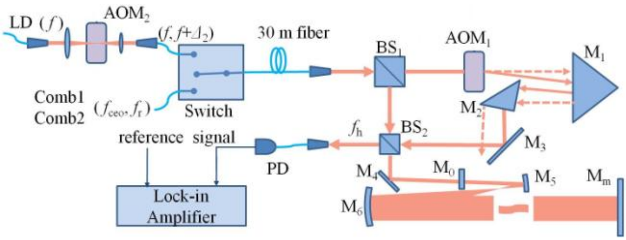

Figure 3: The schematic of the heterodyne interference system using optical combs and a laser diode as the laser source.

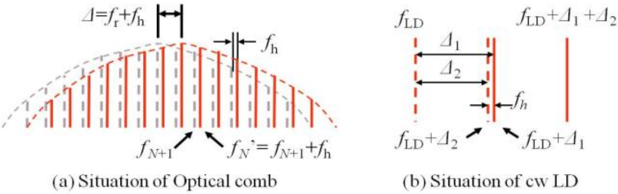

Figure 4 Generated heterdyne signal frequency.

An acoustic-optical modulator (AOM_1) is set in the reference arm to generate the frequency shift $\varDelta_1$, which is can be written as $\varDelta_1=f_r+f_h$, where f_r is the repetition rate, which is tens of megahertz and f_h is tens of kilohertz. The original (k+1)-th mode of the optical comb will interfere with shifted k-th mode, so the heterodyne frequency is f_h (Figure 4(a)). When the cw LD is used as the laser source, another AOM (AOM_2) is set before the interference system to generate a frequency shift $\varDelta_2$,, and $\varDelta_2=f_r$. Both the light beams of optical frequencies f and $f + \varDelta_2$ enter the heterodyne interferometer, so there are four frequencies in the interference system (figure 4 (b)). As a result, the heterodyne frequency is $|\varDelta_1-\varDelta_2|$, which still equals to f_h.

The heterodyne signals are generated when the temporal coherence interference happens. So the optical path difference (OPD) between the two arms of the interferometer should be OPD=mc/nf_r, where m is an integer, c is the light velocity in vacuum, n is the air refractive index. The mirror M_0 is set at the position where OPD = 0, so the distance l under measurement is l=OPD/2.

2.2 Results and conclusion

Two groups of experiments have been done. One is to compare Comb1 with the LD at the distance of 22.478 m (m=15, Δ_1 = 99.9 MH, Δ_2 = 100 MHz, f_h is 100 kHz). The other is to compare Comb2 with the LD at the distance of 22.909 m (m=9, Δ_1=59.0000 MHz, Δ_2 = 58.9286 MHz, and f_h= 71.4 kHz). The time constant of the lock-in amplifier is changed from 1ms to 10 s.

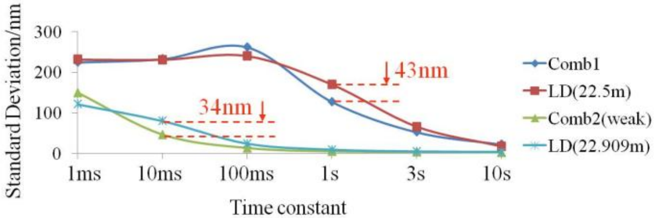

Figure 5 The standard deviations of measurement with the optical combs and the LD.

Figure 5 shows the measurement standard deviation when the time constant is changed from 1ms to 10 s. The measurement stabilities are similar when the light sources are optical combs and the cw LD. The maximum differences are 43 nm (Comb1) and 34 (Comb2), and when the time constant is 3 s, the differences are only 13 nm (Comb1) and 1.5 nm (Comb2). In the experiments of measuring the distance of 22.909 m, the standard deviation is no more than 30 nm when the time constant is longer than 100 ms, and it is less than 10 nm when the time constant is longer than 1 s. The difference between two groups is due to the conditions of experiments for different days.

The preliminary expereiment results show that the stability of measurement is good enough, and the measurement stabilities of the optical comb and the laser diode are similar, so the two laser sourses can be used in one interference system at the same time.

Reference:

[1] Xiaonan Wang, Satoru Takahashi, Kiyoshi Takamasu, and Hirokazu Matsumoto, "Space position measurement using long-path heterodyne interferometer with optical frequency comb," Opt. Express **20**, 2725-2732 (2012)