Absolute Distance Measurements Using the Frequency Comb of a Femtosecond Pulse Laser

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Abstract
The frequency comb of a femtosecond laser is exploited as the wavelength ruler in performing distance measurements by means of multi-wavelength interferometry. For the task, the frequency comb is stabilized by phase-locking the mode spacing and also the absolute frequency offset to the Rb clock of an rf time standard. Then, an external-cavity laser diode (ECLD) is tuned to the stabilized comb so that the absolute value of a given distance is measured by modulating the ECLD as the light source in sweeping and hopping modes. This method enables absolute distance measurements to be conducted with a small uncertainty that can systematically be evaluated in accordance with the SI definition of the metre.

1. Introduction

Multi-wavelength interferometry enables absolute measurement of a distance while it requires devising a tuneable light source capable of providing multiple optical wavelengths with high precision in terms of the uncertainty and linewidth. The advent of the frequency comb technology based on femtosecond pulse lasers has permitted calibrating optical wavelengths with direct traceability to the atomic clock of time standard [1]. And recently, along with the progress of the ultrafast optics, the concept of optical frequency generation (OFG) has been proposed to realize a tuneable monochromatic light source providing accurate wavelengths referenced to the frequency comb of a femtosecond laser. In our investigation, an advanced method of absolute distance measurement is demonstrated relying on the comb-based OFG technology. This method is applicable to industrial applications in that a long distance has to be measured absolutely with sub-wavelength resolution, which cannot be met using commercially available heterodyne or homodyne laser interferometers.

2. Optical frequency generation

The ultrashort pulse train of a femtosecond laser appears as a frequency comb comprised of a large number of evenly spaced quasi-monochromatic light modes in the spectral domain. The frequency comb can be characterized collectively by two independent parameters; the pulse repetition rate f_r and the carrier-offset frequency f_o. Phase-locking both f_r and f_o to the Rb atomic clock of an rf time standard enables all the light lodes to be collectively stabilized as illustrated in Figure 1. An external-locked laser diode (ECLD) is adopted as the working light source with its output frequency being tuned to the frequency comb. Among the many beat signals of different frequencies observed when the ECLD laser is interfered with the frequency comb, the lowest beat signal f_b is extracted through low-pass filtering and also locked to the Rb clock. Thus the frequency of the ECLD laser is expressed as $f_{WL} = i{\cdot}f_r + f_o + f_b$, with uncertainty being 5.8×10^{-12} at 10 s average time within a tunable wavelength range of 16 nm [2].

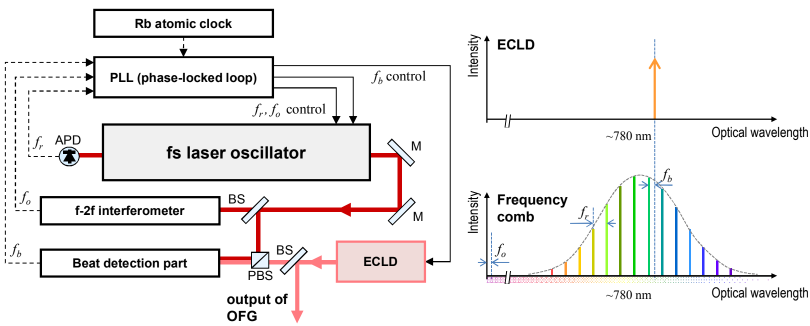

Figure 1. Optical frequency generation (OFG) from the stabilized frequency comb. BS: beam splitter, PBS: polarizing beam splitter, APD: avalanche photodetector.

3. Multi-wavelength interferometer

Multi-wavelength interferometry aims to measure an absolute distance by employing multiple wavelengths collectively using a single optical interferometer setup. For each wavelength λ, the distance is expressed as $L = (\lambda/2)(m + e)$, where m denotes an integer (m=0,1,2,…) and e is the excess fraction ($1>e\geq0$). The excess fraction e can readily be obtained, but the integer m is not the case due to the 2π-ambiguity of optical interferometry. However, combining all the individual measurement results leads to the simultaneous equations of $L = (\lambda_1/2)(m_1 + e_1) = \ldots = (\lambda_N/2)(m_N + e_N)$, where the subscript N indicates the total number of wavelengths in use. Since all of m_j must be positive integers, the absolute distance L can be determined with the measured values of e_j (j=0,1,…,N) by means of iterative numerical computation [2,3].

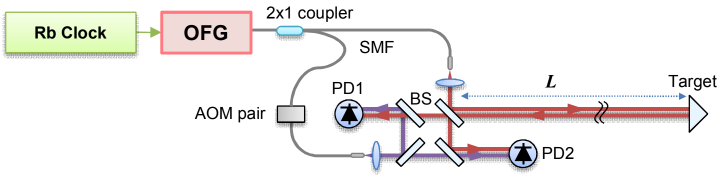

Figure 2. Optical layout of the multi-wavelength interferometer set up in this investigation with an ECLD laser being tuned to the frequency comb stabilized to the Rb atonic clock. AOM: acoustic-optical modulator, BS: beam splitter, PD: photodetector, SMF: single-mode fiber.

Figure 2 shows the multi-wavelength interferometer configured for absolute distance measurements [3]. For each wavelength, the heterodyne phase-measuring principle is used independently. No polarization-based beam splitting is used to minimize the periodic error caused by polarization leakage. A pair of acousto-optic modulators (AOM) is adopted for frequency heterodyning and two photo-detectors (PD1 and 2) are installed to detect the resulting interference signals. The four wavelengths, 770.204349 nm, 779.953524 nm, 780.203668 nm, and 780.206961 nm are generated by modulating the ECLD light source. The particular set of selected four wavelengths are chosen so as to make sure that the non-ambiguity range of the measured distance far exceeds the uncertainty range of the measurement. This requires proper initial estimation of the absolute distance being measured, which can effectively be conducted by sweeping the wavelength by modulating the ECLD laser continuously for a predetermined wavelength tuning interval. An actual measurement data is summarized in Table 1, in which a distance of ~1.2 m was measured. The refractive index of air is considered to correct the wavelength errors caused by temperature, relative humidity, pressure, and CO_2 contents [4]. A thorough error analysis was conducted in faithful accordance with the ISO-recommended guidelines to confirm that the overall measurement uncertainty turns out to be less than 17 nm when measuring distances up to tens of meters, with major contribution arising from the uncertainty in estimating the true value of the refractive index of air .

Table 1. An exemplary measurement data of an ~1 m distance.

Vacuum wavelength	Excess fraction	Refractive index of air
780.206961 nm	0.6983	1.000263346
780.203668 nm	0.3302	1.000263345
779.953524 nm	0.1675	1.000263347
770.204349 nm	0.7146	1.000263410
Absolute distance: 1195.287863 mm		

4. Conclusion

The concept the absolute multi-wavelength interferometer exploiting the frequency comb of a femtosecond laser as the wavelength ruler is found effective and capable of providing precision needed in many industrial applications. The frequency of the ECLD light source stabilized to the Rb clock of a rf time standard yields a high level of uncertainty of 5.8×10^{-12} at 10 s averaging time. Absolute distance measurements performed using four selected different wavelengths offers an uncertainty of 17 nm when measuring an ~1 m distance, which can be well certified with direct traceability to the SI definition of the metre.

References:

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