Real-time absolute distance measurement using multi-wavelengths referenced to the frequency comb

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We demonstrate exploiting multiple optical wavelengths referenced to the frequency comb of an Er-doped fiber femtosecond laser as a means to realize the real-time absolute distance measurement.

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1. Introduction

The frequency comb of a femtosecond laser has brought a new breakthrough in bridging the large gap between the laser frequencies and microwave time standards, which was also a long-cherished desire in the field of length and distance metrology due to the time reference definition of the metre. To measure absolute distances with an extended non-ambiguity range, multiple wavelengths need to be employed simultaneously in parallel or in sequence. This consequently requires either a tunable laser source or multiple laser sources to generate stable, accurate optical wavelengths over a wide spectral range in a discrete way to perform multi-wavelength interferometry [1]. For the purpose, multi-wavelength interferometers referenced to the frequency comb has been proposed thereafter and applied for different forms of absolute distance metrology such as absolute calibration of gauge blocks [2], two-wavelength interferometer, spectrally resolved interferometer and multi-heterodyne interferometer [3,4]. They have been sensitive to time dependent environmental variations because they inherently rely on sequentially generated wavelength at different time slot. Here, in this paper, we report to exploit four wavelengths in parallel referenced to the frequency comb to perform absolute distance measurement in real-time for uses of high-speed control such as formation flying multiple satellites or precision positioning of semiconductor stages.

2. Principle and experimental configuration

Fig. 1 shows the overall system configuration for the real-time absolute distance measurement. The frequency comb of the Er-fiber femtosecond laser, having a 50 nm spectral bandwidth centered at 1550 nm, was stabilized to the Rb clock of a time standard. The AWG (Array Waveguide Grating) filters the frequency comb into several channels having 100 GHz bandwidth and thereafter PDs detect the beat frequencies between the frequency comb and the output beam of the DFB lasers at each channel. Four DFB lasers are precisely phase-locked to the pre-determined reference frequency by well-established PLL technique. Finally, a 4x1 fiber coupler combines the resulting frequency-stabilized four output beams and transfers them to the absolute distance measuring interferometer. Two acousto-optic modulators (AOMs) are used to generate slightly different optical frequencies for heterodyne phase detection. The light from the frequency comb referenced multi-channel light source experiences two different optical paths and recombined at a beam splitter. Highly sensitive photodiodes are installed to detect the resulting interference signals at four different wavelengths. Precision phase-meters are used to measure the phase differences between interference signals with four different wavelengths as required for absolute distance measurements. The maximum sampling rate and resolution of the phase-meter is 40 kHz and 0.31 mrad. The phase detection uncertainty is 1.84 mrad which corresponds to the measurement uncertainty of 2.8 nm in length.

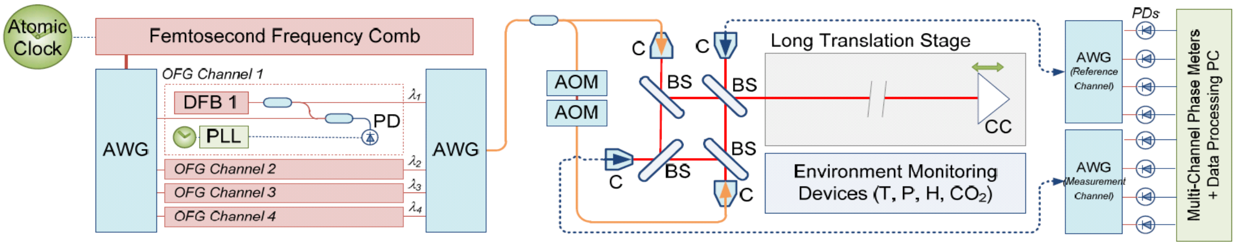

Fig. 1 Real-time absolute distance measurement referenced to optical frequency comb of a femtosecond pulse laser. Abbreviations are, AWG: array waveguide grating, OFG: optical frequency generator, DFB: distributed feedback laser, PLL: phase-locked loop, AOM: acousto-optic modulator, BS: beam splitter, C: collimator, CC: corner cube, PD: photo-detectors

3. Experimental result and discussion

Fig. 2 shows the experimental results of the absolute distance measurement. A particular set of four wavelengths was chosen in an optimized way to extend the non-ambiguity range to several meters (See Fig. 2 (a)). The phase information of the each wavelength is measured in real-time by the interferometer as shown at Fig. 2. (b). By applying the principle of the multi-wavelength interferometer with the following equation, the absolute distance was successfully measured and compared with the conventional laser interferometer while linear stage was scanned (See Fig. 2(c)). The measurement is robust to time-dependent environmental changes which is not easy to determine the absolute distance in case of using sequentially generated wavelengths. The resulting uncertainty of the absolute distance measurement was found less than 20 nm in accordance with the ISO-recommended guidelines.

$$L = \frac{\lambda_1}{2}(m_1 + e_1) = \cdots = \frac{\lambda_N}{2}(m_N + e_N) \quad (1)$$

With unique advantages of high speed, high precision, absolute distance measurement, and direct traceability to the time standard, this approach could find its applications in high precision engineering and space missions.

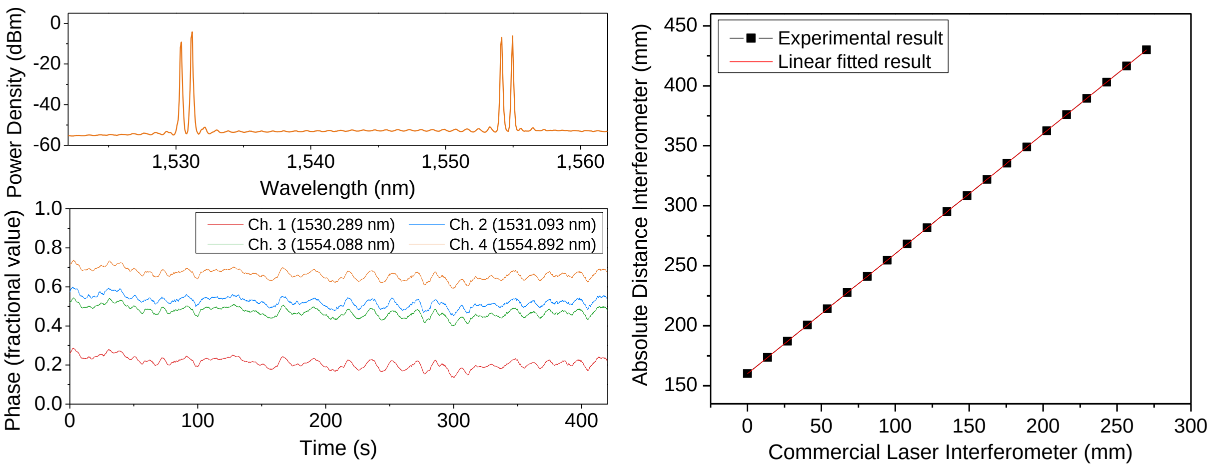

Fig. 2. Multiple wavelengths generation and absolute distance measurement in real-time referenced to the frequency comb (a) simultaneous generation of four wavelengths, (b) real-time phase measurement result using multi-channel phase-meters, (c) comparison of measurement results with conventional laser interferometers.

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