Key Engineering Materials Vol. 625 (2015) pp 322-325 Online: 2014-08-11
© (2015) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/KEM.625.322

Length Traceability using Optical Frequency Comb

Dong Wei [1, a], Kiyoshi Takamasu [2,b] and Hirokazu Matsumoto [2,c]

[1] Nagaoka University of Technology, 1603-1 Kamitomioka town, Nagaoka City, Niigata Prefecture, Japan 940-2188

[2] The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo, Japan 113-8656

[a] weidong@mech.nagaokaut.ac.jp, [b] takamasu@pe.t.u-tokyo.ac.jp, [c] hi.matsumoto@nanolab.t.u-tokyo.ac.jp

Keywords: Length measurement, Interferometry, Length traceability, Optical frequency comb, Length standard

Abstract High-precision length measurements are strongly demanded for not only industry requirements and science purposes.In 2009, a femtosecond optical frequency comb (FOFC) was adopted in Japan as the national standard tool for measuring length. Recently, numerous studies have focused on FOFC-based high-precision length measurement because this approach offers the possibility of development of a ultimate green length traceability system. A single-wavelength helium–neon (He–Ne) laser was used as a length standard. An FOFC emits discrete pulse-train-shaped light. This markedly different characteristic exists between a He-Ne laser and an FOFC is the reason for the challenge. Previous attempts to challenge this problem have not been satisfactory. This has limited the development and applications of FOFC-based length measurement.

In this work, we review our efforts of FOFC-based high-precision length measurement toward developing an ultimate green length traceability system.

Introduction

Since the invention of femtosecond optical frequency comb (FOFC), its great potential for length measurement and traceability has been recognized, but the challenge [1-4] for achieving length measurements with FOFC does not end today.

In 2009, an FOFC was adopted in Japan as the national standard tool for measuring length. The ability to measure real-time, high-accuracy and long-range length information opened the door to the traceability of the meter over an optical fiber network. The possibility of using the adjacent pulse repetition interval length (APRIL) as a length ruler was also recognized [5]. However, the FOFC has not reached its full potential, since there is as yet no easy-to-use standard technology directly linked to the FOFC length standard tool for measurement.

In this paper, we describe our previous FOFC-based length measurement and related works [5-13]. We will focus three facts: the length scale, the temporal coherence function of an FOFC and the length expression. These are our proposal that directly linked to the FOFC length standard tool to realize the meter. Other efforts [14-16] have also been performed using FOFCs to measure and/or transfer length standards.

This paper is organized as follows. First, a short literature review is performed in Section 2. Second, the basic facts for FOFC-based length measurement, including the length scale, the temporal coherence function of an FOFC and the length expression, are described in Section 3. Then, the basic scheme and the result of a preliminary experiment are shown in Section 4. Finally, the main conclusions are summarized in Section 5.

Literature Review

As already reported in Ref. [11, 12], it was found that distance can be measured as a function of the APRIL by determining two parameters from the interference fringes of multiple pulse trains. The point is how to characterize the pulses in the proposed multiple Michelson interferometer. How to encode the electric field of an optical pulse was reviewed in Ref. [17]. Spectrograph, tomography and interferometry can be used to encode the electric field of an optical pulse. Spectrograph [14, 16] and interferometry (including intensity correlation [2-4, 18] and interferometric correlation [11, 12]) were been used to characterize optical pulses. The difference between intensity correlation and interferometric correlation is the presence or absence of phase information which can be used for the high resolution measurement.

Principles

For convenience of explanation, we start with the features of an FOFC. For details about FOFC see Ref. [19].

FOFC is an ultra-steady pulse laser. Pulse train generated by an FOFC. In the time-domain, a carrier pulse propagates with a carrier frequency angle ω_c. A phase difference exists between the phase velocity and the group velocity; for a packet comprising repeated electric field pulses with a pulse repetition period T_R, the phase difference or "slipping" between the carrier phase and the carrier envelope phase is $\Delta\varphi_{ce}$ at any given instant of time. In the frequency domain, a mode-locked FOFC has a large number (of the order of 10^6) of frequency components that are spaced at equal intervals with a repetition frequency of $f_{rep} = 1/T_R$. Moreover, the entire FOFC is shifted from zero frequency by an offset frequency given by $f_{CEO} = f_{rep} \times \Delta\varphi_{ce}/2\pi$.

In this section we will answer three questions. The first one is what should be used as a length scale for FOFC-based length measurement. The second one is why different pulse trains can interfere with each other. The third one is how to realize the length measurement by using APRIL.

Length Scale [5]. The possibility of using an APRIL as a length scale was investigated in Ref. [5]. The idea can be understood as follows. Currently, the highest absolute frequency stability that can be achieved by an FOFC is about 10^{-18} order. Because an FOFC is a set of superposition of different single frequencies, if each frequency is stable, the FOFC (of course, an APRIL) is also steady at the same level.

Temporal Coherence Function of an FOFC [7]. It can be understood that the interference phenomenon observed is due to comb-like spectrum.

Realization of length measurement [11-13]. An arbitrary and absolute distance L can be expressed as a function of APRIL δ by the following equation.

$$L = \delta \times (N + \Delta) . \qquad (1)$$

Here, N and Δ are the integral and the excess fractional parts, respectively. The distance can be measured by determining two values N and Δ.

Preliminary Experiment

An intensity-based two-color method was performed [20]. This mechanism is used for measurement of N and Δ in the following manner. [Fig. 1]. The pulse (center frequency is 1560 nm) is incident on a periodically poled lithium niobate (PPLN) that generates a pulse with a doubled frequency (center frequency is 780 nm). Two pulses to be recorded are introduced to a multiple Michelson interferometer. The peaks of the interferometric correlations of two pulses are measured. N and Δ can be obtained from the measured peaks.

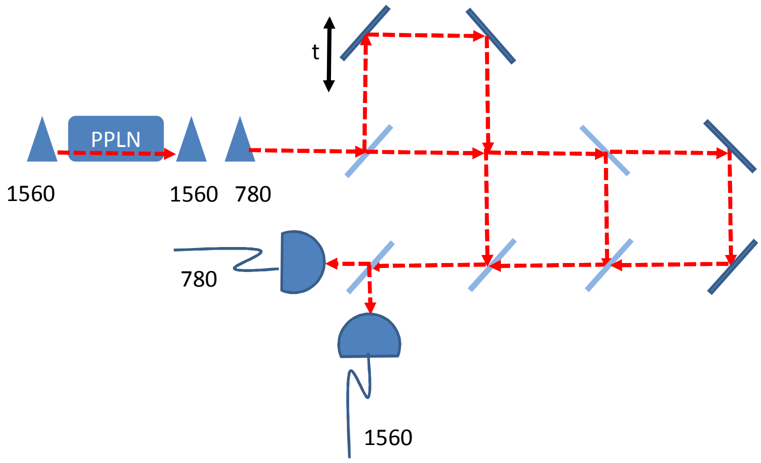

Fig. 1. Principle of an intensity-based two-color method.

Summary

For more than five years, we have been at the forefront of the development of FOFC-based length measurement method. Adapting our efforts to realize length traceability via an optical fiber network to respond to new needs from industrial application is still a critical challenge.

An overview of our efforts has been reviewed. The points of our ideas include what should be used as a length scale for FOFC-based length measurement, why different pulse trains can interfered with each other and how to realize the length measurement by using APRIL.

FOFC-based length measurement remains a critical challenge and further theoretical and technical developments are required, especially in light of the fierce global competition of production.

Acknowledgments

This research work was financially supported by Grant-in-Aid for Young Scientists (B) Grant Number 25820171. H. M. was supported by the “Development of System and Technology for Advanced Measurement and Analysis” Program at the Japan Science and Technology Agency.

References

[1] H. Matsumoto, X. Wang, K. Takamasu, and T. Aoto, Absolute Measurement of Baselines up to 403 m Using Heterodyne Temporal Coherence Interferometer with Optical Frequency Comb, Appl. Phys. Expr. **5** (2012) 046601.

[2] C. Narin, T. Satoru, T. Kiyoshi, and M. Hirokazu, A new method for high-accuracy gauge block measurement using 2 GHz repetition mode of a mode-locked fiber laser, Meas. Sci. Technol. **23** (2012) 054003.

[3] X. Wang, S. Takahashi, K. Takamasu, and H. Matsumoto, Space position measurement using long-path heterodyne interferometer with optical frequency comb, Opt. Express **20** (2012) 2725-2732.

[4] X. Wang, S. Takahashi, K. Takamasu, and H. Matsumoto, Spatial positioning measurements up to 150 m using temporal coherence of optical frequency comb, Precis. Eng. **37** (2013) 635-639.

[5] D. Wei, K. Takamasu, and H. Matsumoto, A study of the possibility of using an adjacent pulse repetition interval length as a scale using a Helium–Neon interferometer, Precis. Eng. **37** (2013) 694-698.

[6] D. Wei and H. Matsumoto, Measurement accuracy of the pulse repetition interval-based excess fraction (PRIEF) method: an analogy-based theoretical analysis, J. Eur. Opt. Soc-Rapid Publ. **7** (2012) 12050.

[7] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Analysis of the temporal coherence function of a femtosecond optical frequency comb, Opt. Express 17 (2009) 7011-7018.

[8] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Simultaneous Observation of High Temporal Coherence between Two Pairs of Pulse Trains Using a Femtosecond-Optical-Frequency-Comb-Based Interferometer, Jpn. J. Appl. Phys. 48 (2009) 070211.

[9] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Experimental observation of pulse trains' destructive interference with a femtosecond optical frequency-comb-based interferometer, Opt. Lett. 34 (2009) 2775-2777.

[10] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Femtosecond optical frequency comb-based tandem interferometer, J. Eur. Opt. Soc-Rapid Publ. 4 (2009) 09043.

[11] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Theoretical Analysis of Length Measurement Using Interference of Multiple Pulse Trains of a Femtosecond Optical Frequency Comb, Jpn. J. Appl. Phys. 50 (2011) 022701.

[12] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Time-of-flight method using multiple pulse train interference as a time recorder, Opt. Express 19 (2011) 4881-4889.

[13] D. Wei, K. Takamasu, and H. Matsumoto, Synthetic adjacent pulse repetition interval length method to solve integer ambiguity problem: theoretical analysis, J. Eur. Opt. Soc-Rapid Publ. 8 (2013) 13016.

[14] CoddingtonI, W. C. Swann, NenadovicL, and N. R. Newbury, Rapid and precise absolute distance measurements at long range, Nat. Photon **3** (2009) 351-356.

[15] K.-N. Joo and S.-W. Kim, Absolute distance measurement by dispersive interferometry using a femtosecond pulse laser, Opt. Express **14** (2006) 5954-5960.

[16] S. A. van den Berg, S. T. Persijn, G. J. P. Kok, M. G. Zeitouny, and N. Bhattacharya, Many-Wavelength Interferometry with Thousands of Lasers for Absolute Distance Measurement, Phys. Rev. Lett. **108** (2012) 183901.

[17] I. A. Walmsley and C. Dorrer, Characterization of ultrashort electromagnetic pulses, Adv. Opt. Photon. **1** (2009) 308-437.

[18] J. Jin, Y. Kim, Y. Kim, and S. Kim, Absolute Distance Measurements Using the Optical Comb of a Femtosecond Pulse Laser, Int. J. Precis. Eng. Manuf. **8** (2007) 22-26.

[19] F. Helbing, G. Steinmeyer, and U. Keller, Carrier-envelope offset phase-locking with attosecond timing jitter, IEEE J. Quantum Electron. **9** (2003) 1030-1040.

[20] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto: submitted to Jpn. J. Appl. Phys. (2013)

Precision Engineering and Nanotechnology V
10.4028/www.scientific.net/KEM.625

Length Traceability Using Optical Frequency Comb
10.4028/www.scientific.net/KEM.625.322

DOI References
[1] H. Matsumoto, X. Wang, K. Takamasu, and T. Aoto, Absolute Measurement of Baselines up to 403 m Using Heterodyne Temporal Coherence Interferometer with Optical Frequency Comb, Appl. Phys. Expr. 5 (2012) 046601.
http://dx.doi.org/10.1143/APEX.5.046601
[2] C. Narin, T. Satoru, T. Kiyoshi, and M. Hirokazu, A new method for high-accuracy gauge block measurement using 2 GHz repetition mode of a mode-locked fiber laser, Meas. Sci. Technol. 23 (2012) 054003.
http://dx.doi.org/10.1088/0957-0233/23/5/054003
[3] X. Wang, S. Takahashi, K. Takamasu, and H. Matsumoto, Space position measurement using long-path heterodyne interferometer with optical frequency comb, Opt. Express 20 (2012) 2725-2732.
http://dx.doi.org/10.1364/OE.20.002725
[4] X. Wang, S. Takahashi, K. Takamasu, and H. Matsumoto, Spatial positioning measurements up to 150 m using temporal coherence of optical frequency comb, Precis. Eng. 37 (2013) 635-639.
http://dx.doi.org/10.1016/j.precisioneng.2013.01.008
[5] D. Wei, K. Takamasu, and H. Matsumoto, A study of the possibility of using an adjacent pulse repetition interval length as a scale using a Helium-Neon interferometer, Precis. Eng. 37 (2013) 694-698.
http://dx.doi.org/10.1016/j.precisioneng.2013.02.001
[7] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Analysis of the temporal coherence function of a femtosecond optical frequency comb, Opt. Express 17 (2009) 7011-7018.
http://dx.doi.org/10.1364/OE.17.007011
[8] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Simultaneous Observation of High Temporal Coherence between Two Pairs of Pulse Trains Using a Femtosecond-Optical-Frequency-Comb-Based Interferometer, Jpn. J. Appl. Phys. 48 (2009) 070211.
http://dx.doi.org/10.1143/JJAP.48.070211
[9] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Experimental observation of pulse trains' destructive interference with a femtosecond optical frequency-comb-based interferometer, Opt. Lett. 34 (2009) 2775-2777.
http://dx.doi.org/10.1364/OL.34.002775
[11] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Theoretical Analysis of Length Measurement Using Interference of Multiple Pulse Trains of a Femtosecond Optical Frequency Comb, Jpn. J. Appl. Phys. 50 (2011) 022701.
http://dx.doi.org/10.7567/JJAP.50.022701
[12] D. Wei, S. Takahashi, K. Takamasu, and H. Matsumoto, Time-of-flight method using multiple pulse train interference as a time recorder, Opt. Express 19 (2011) 4881-4889.
http://dx.doi.org/10.1364/OE.19.004881
[13] D. Wei, K. Takamasu, and H. Matsumoto, Synthetic adjacent pulse repetition interval length method to solve integer ambiguity problem: theoretical analysis, J. Eur. Opt. Soc-Rapid Publ. 8 (2013) 13016.
http://dx.doi.org/10.2971/jeos.2013.13016

[14] CoddingtonI, W. C. Swann, NenadovicL, and N. R. Newbury, Rapid and precise absolute distance measurements at long range, Nat. Photon 3 (2009) 351-356.
http://dx.doi.org/10.1038/nphoton.2009.94
[16] S. A. van den Berg, S. T. Persijn, G. J. P. Kok, M. G. Zeitouny, and N. Bhattacharya, Many-Wavelength Interferometry with Thousands of Lasers for Absolute Distance Measurement, Phys. Rev. Lett. 108 (2012) 183901.
http://dx.doi.org/10.1103/PhysRevLett.108.183901