High-resolution time-of-flight measurement using a femtosecond pulse laser

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The conventional time-of-flight measurement which is limited by several milimeter resolutions is enhanced by adopting a femtosecond laser with high-precision pulse repetition-rate control. The high resolution performance is evaluated in laboratory environment by comparison with commercial laser interferometer resulting in 10 nm (at 5 ms) and long-distance measurement in ambient environment is also demonstrated which shows 150 nm (at 5 ms) resolution over 0.7 km. An indirect analysis based on Allan deviation using lock-in control signal shows achievable resolution could reach up to 1 nm (at 1 s) in free-space environment.

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1. Introduction

The time-of-flight (TOF) principle measuring the traveling time of long propagating pulse between instrument and target has been most fundamental and widespread technology in distance measuring system owing to its superior advantages in terms of maximum measurable range up to hundreds of kilometers and even more. The TOF measurement has been only adopted to industrial applications covering from large-scale 3D coordinate measurement to geodetic survey but also appeals to space mission including satellite laser ranging (SLR), lunar laser ranging (LLR) range-resolved LIDAR system to mention a few [1]. Especially, in case of the future multi-satellite project, the high-resolution distance measurement technology is classified as key technology to tightly configure formations between space crafts [2]. For instance, Darwin project which is planed to investigate earth-like planet needs several nanometer resolution over hundreds of meter and XEUS(X-Ray Evolving Universe Spectroscopy Mission) which will be used for detection of X-ray glow in the space needs micrometer resolution over hundreds of meter. To satisfy the challenging performance, femtosecond laser based absolute distance measurement is proposed and realized exploiting high frequency stability, wide optical spectrum and extremely short pulse characteristics of the light source. Even though the conventional TOF shows very long distance measurement capability, the achievable resolution of conventional TOF measurement, however, reached only a few millimeters at best. This limitation attributes to conversion of optical pulse to microwave pulse in the detection part of which state-of-the art bandwidth is available at picoseocnd range. In this paper, to overcome limited resolution of conventional TOF, we present a way to directly extract distance information in optical domain by using of a femtosecond pulse laser and nonlinear characteristics of second harmonic generation crystal with timing precision of less than 1 fs, which corresponds to sub-micrometer resolution in distance. The high resolution performance is also evaluated experimentally in ambient environment.

2. Main Principle

The high-resolution TOF consists of balanced optical cross-correlator (BCC) and Michelson interferometer in which measurement arm is relatively long compared with the reference arm (Fig. 1). The measurement and reference pulses are reflected at each mirror located at the ends of the arms and two pulses are recombined at the BCC. The BCC is used for precise pulse timing detection which enables the timing resolution less than 1 fs between two orthogonally polarized pulses [3]. The key idea of the BCC is convert timing difference between two pulses into voltage signal (inset graph in Fig.1).

Owing to the different path length of the two arms, the timing difference, Δt between two pulses is described as $\Delta t = 2D/c - m/f_{rep}$ where, where, D is target distance and m is the integer number, f_{rep} is pulse repetition rate of the femtosecond laser. The Δt is continuously monitored by the BCC and eventually locked to be zero by controlling pulse repetition rate, frep. Finally, D is determined by frep measurement described by

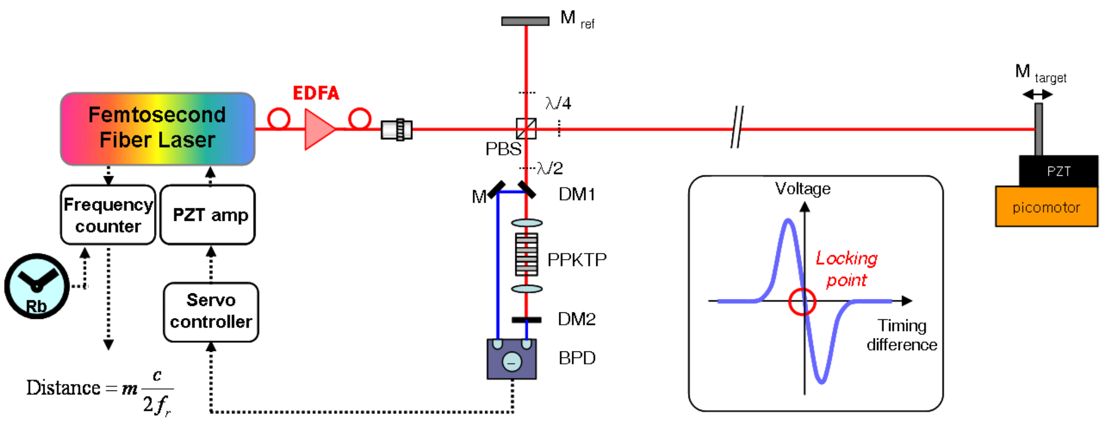

Fig. 1 The high-resolution TOF using a fiber femtosecond laser and a balanced optical cross-correlator. The femtosecond laser pulses are amplified by EDFA. The inset graph denotes voltage signal with respect to timing difference which is used for feedback control locking the timing difference into zero. The target mirror is attached on PZT and picomotor for evaluation of performance. Abbreviations are; EDFA: Er-doped fiber amplifier, PBS: polarized beam splitter, DM: dichroic mirror1(2) , PPKTP: periodically poled potassium titanyl phosphate, BPD: balanced photodetector.

following equation.

$$D = c \cdot \frac{m}{2 f_{rep}}$$

The integer number, *m* is determined by stroboscopic technique [3]. The f_{rep} is measured by frequency counter which is referenced to atomic clock traceable to frequency standard and the frep measurement shows high precision up to 10^{-12}. Therefore high resolution distance measurement is enabled by frequency measurement.

3. Experimental Results

The performance of the TOF measurement is evaluated in short range of 1.5 meter by comparing with commercial laser interferometer. Fine displacements of 100 nm step are applied to target mirror by using PZT and 30 steps are measured by the TOF system and commercial laser interferometer, simultaneously. The difference and linearity between two data showed within 20 nm and 0.9998, respectively. In addition, to evaluate resolution at long distance, 0.7 km was measured. The distance was modulated by using of PZT at 10 Hz with 150 nm amplitude. The modulated 150 nm was clearly shown.

4. Conclusions

We demonstrated high-resolution TOF measurement using a femtosecond pulse laser which can be applied to future space missions requiring high-resolution over long distances. To acquire reliable, robust laser source against to external environmental attenuation and to deliver enough power of the pulse at long distance, all-fiber femtosecond laser and EDFA system were developed. By locking the time-difference into zero, the distance information is measured precisely by frequency measurement which is repetition rate of femtosecond laser. The frequency is measured by frequency counter referenced to atomic clock traceable to frequency standard. To evaluate the performance of the TOF measurement, at short range of 1.5 m, we compared the distance result with conventional laser interferometer under 100 nm steps of target mirror. The ~0.7 km long distance measurement was conducted and 150 nm with 10 Hz distance modulation was successfully measured.

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