Advanced Optical Metrology Using Ultrashort Pulse Lasers

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Emerging possibilities of using ultrashort pulse lasers as a new light source for advanced metrology are addressed in comparison to traditional sources such as CW lasers and white Emphasis is on explaining various principles of absolute distance interferometry that become practical by exploiting the unique nature that a train of ultrashort pulses is a phase-locked combination of a large number of monochromatic laser lines evenly spaced over a wide range. In that context, adopting a single ultrashort pulse laser offers many new opportunities performing absolute distance measurements with sub-wavelength resolutions over extensive ranges. It is also discussed that the new light source allows one to improve the measuring performances of other fields of optical metrology such as large-scale surface profiling.

Key Words: Optical metrology, Interferometry, Distance measurement, Ultrashort pulse laser, Femtosecond pulse laser

1. Introduction

During a 1 fs (femtosecond = 10^{-15} s) period of time, light propagates in the air over a distance of 0.3 μm that merely amounts to half the wavelength of visible light. These days, as a result of the progress made in laser technology during last decades, ultrashort pulse lasers of less than 10 fs pulse width are available with a single pulse encompassing only a few cycles of the carrying wave. These ultrashort pulses as appearing in the time domain is likely to enhance the measuring accuracy of existing time-of-flight techniques with a few orders of magnitude particularly for long range distance measurements for terrestrial and satellite applications. However, the remarkable reduction in the pulse width is not directly reflected in the measured resolution and accuracy, mainly due to the speed limitation on the available detector electronics. Pulse broadening caused by dispersion of light pulses in the air also restricts the performance improvement that could be made in time-of-flight measurements.

A remarkable feature of ultrashort laser pulses when observed in the optical frequency domain is that they are in fact a mode-locked combination of a quite large number of quasi-monochromatic discrete laser lines that are uniformly distributed over a wide spectral bandwidth in the optical frequency domain.[1] The pulse width Δt and the spectral bandwidth $\Delta\nu$ maintain the relationship of $\Delta t \cdot \Delta\nu = K$ where the constant K equals 0.32 and 0.44 for transform-limited sech^2 and Gaussian pulses, respectively. It is typical that a 10 fs pulse has a spectral bandwidth of 100 nm, being composed of about a million monochromatic lines with a repetition frequency of 100 MHz. The overall frequency distribution of an ultrashort pulse laser is called the optical comb, which works as a precision ruler for advanced metrology. All the light lines within a given optical comb can collectively be frequency-stabilized by phase-locking two rf-signals, the repetition rate f_r and the carrier offset frequency f_o, to the frequency standard of Cs or Rb clock. The repetition rate f_r is readily monitored by using a photodetector, while the f-2f interferometer needs to be incorporated to detect the carrier offset f_o.[2] The frequency stabilization allows any light line within the optical comb can be expressed as $f = Nf_r + f_o$ with N being an integer, of which uncertainty can be traced with high precision to the frequency standard in use. Figure 1 shows a typical construction of optical frequency synthesizer, in which an ECLD(External Cavity Laser Diode) is used as the working laser with its frequency being locked to a optical comb of femtosecond pulse laser generated from a Ti;Sapphire

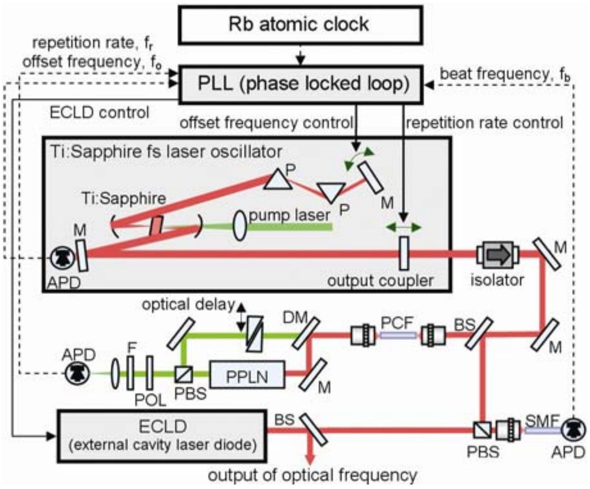

Fig 1 Construction of a optical frequency synthesizer using the optical comb of a Ti:Sapphire femtosecond laser. M: mirror, P: prism, APD: avalanche photodetector, BS: beam splitter, F: spectral filter, PBS: polarizing beam splitter, DM: dichroic mirror, PCF: photonic crystal fiber, POL: polarizer, SMF: single mode fiber, PPLN: periodically poled lithium niobate.

crystal.[3,4] Recently optical frequency synthesizer based on single mode amplification has been also reported. [5]

2. Absolute distance measurements

The task of absolute distance measurements aims to determine distances straightway up to extensive ranges. The widely used CW laser interferometers based on homodyne or heterodyne principles are not suitable for the task since they rely on continuous accumulation of incremental/decremental movements of the target. Enlarging the equivalent wavelength by means of grazing incidence or two-wavelength synthesis is not enough to satisfy usual industrial demands on ranges and resolutions. Multi-wavelength interferometry with continuous wavelength modulation using a tunable diode offers relatively long ranges of absolute measurements, but its current practice has not yet reached the precision of relative measurements using homodyne or heterodyne CW laser interferometry. Multi-wavelength interferometry using multiple discrete sources of different wavelengths is considered the most appropriate, but it requires at least three separate monochromatic CW laser sources whose frequencies should be stabilized independently to the well-defined absorption bands of atoms or molecules. As results, no convenient tools of absolute distance measurements are commercially available that can be used for general purposes of precision engineering.

The advent of femtosecond pulse lasers has prompted various efforts to investigate new possibilities of absolute distance measurements which were not possible with precedent light sources. The measurement distance was notably extended without any periodic ambiguity by means of synthetic wavelength interferometry utilizing a femtosecond laser, which was carried out in the radio-frequency domain using a sequence of higher harmonics of the repetition rate.[6] Adopting ultrashort pulse lasers also allows one to perform the principle of dispersive interferometry of absolute distance measurements that is applicable basically to most of two-arm interferometers,[7] which for convenience will be explained with regard to a Michelson type interferometer shown in Figure 2. The light source is a Ti:Sapphire laser that emits a pulse train of ~10 fs pulse duration at a repetition rate of 75 MHz. The pulse train constitutes an optical comb spanning a spectral width of 80 THz about a central frequency of 375 THz in the frequency domain. Each mode of the optical comb is quasi-monochromatic with a line width of less than 1 MHz, bearing a temporal coherence length of ~150 m. The reference mirror M_R is fixed stationary while the measurement mirror M_M is movable along the optical axis of the measurement beam. The interference intensity between the reference and measurement beams is observed by use of a spectrometer that consists of a line grating and a line array of 3648 photodetectors. A FPE(Fabry-Perot Etalon) made from fused silica with 2.0 mm thickness is put before the spectrometer, of which the resonance filtering function trims down the mode density of the comb so that only ~3 filtered consecutive modes are selectively picked out to fall on each photodetector of the spectrometer.

Test results showed that the use of femtosecond laser pulses allows the non-ambiguity range to be extended to ~1.46 mm with a measuring resolution of 7 nm. The minimum measurable distance was constrained to a range of 5 µm, and the maximum measurable distance was extended to 0.89 m in association with a Fabry-Perot Etalon for absolute distance measurements. The method was applied to the thickness measurement of glass plates, of which overall measurement uncertainty was estimated to be in the level of one part in 10^5.(Ref. 8) The exploitation of a femtosecond laser for the dispersive interferometry as attempted in this investigation permits producing an abundance of interference signals of monochromatic frequencies simultaneously. This advantage results in a significant extension of the measurable range far beyond the low-coherence limit of short pulses with no need of time-delay line of mechanical scanning, which may also finds applications in the field of Fourier interferometry for spectroscopy and spectral interferometry in ultrafast technology.

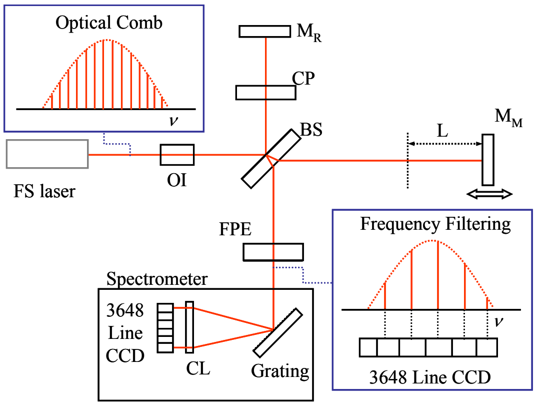

Fig 2 Dispersive interferometer using femtosecond laser pulses. FS laser: femtosecond laser; OI: optical isolator; BS: beam splitter; CP: dispersion compensation plate; FPE: Fabry-Perot etalon; M_R: reference mirror; M_M: measurement mirror; CL: collimating lens. Inlets show the relative line density of the optical comb before and after filtering.

Another approach is to implement the principle of multi-wavelength interferometry by exploiting a femtosecond pulse laser to perform the task of absolute distance measurements with particular emphasis on enhancing measuring accuracy in medium ranges.[4, 9,10] The ultrashort pulse laser provides an optical frequency comb, which is used as the wavelength ruler after being stabilized to an Rb clock of frequency standard. A temporal scheme of multi-wavelength interferometry is then demonstrated by tuning an external cavity laser diode consecutively to the pre-selected light modes of the optical comb. This new approach allows one to measure absolute distances with high precision traceable to the definition of time, providing a great level of improvement in the measuring accuracy of absolute distances particularly for industrial uses. The concept of optical frequency synthesizer exploiting the optical frequency comb of a femtosecond pulse laser was constructed for the task of absolute distance measurements as illustrated in Figure 3. All the light modes of the optical comb were then stabilized by locking both the repetition rate and the carrier offset frequency to a commercially available Rb clock of frequency standard. To the wavelength ruler, an external cavity diode laser was tuned consecutively to provide a sequence of selected wavelengths needed to implement the calibration practice on the basis of multi-wavelength interferometry. The wavelength uncertainty finally achieved was 1.9 × 10^{-10}, which permits the gauge

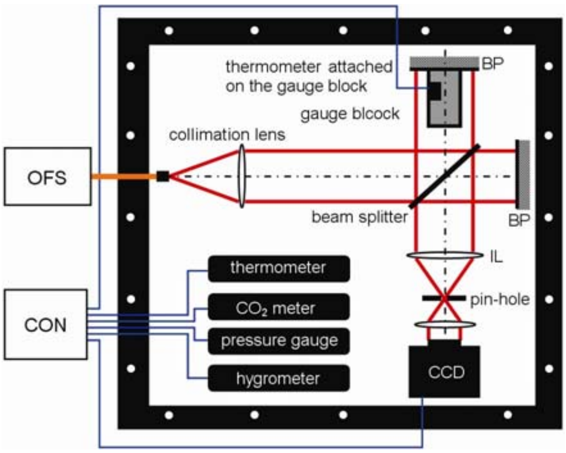

Fig. 3 Optical configuration of the gauge block interferometer. OFS: optical frequency synthesizer, CON: controller, BP: base plate, IL: imaging lens

block calibration to be implemented with no significant error contributions from the source. Actual limitation in length measurement lies in Edlen's formula whose individual uncertainty reaches 1.3 × 10^{-8} at most even with precise monitoring of the environmental parameters. This result demonstrates a successful industrial application of the optical frequency synthesis employing a femtosecond laser, which offers many possibilities of carrying out precision length metrology with traceability to the well-defined international definition of time.

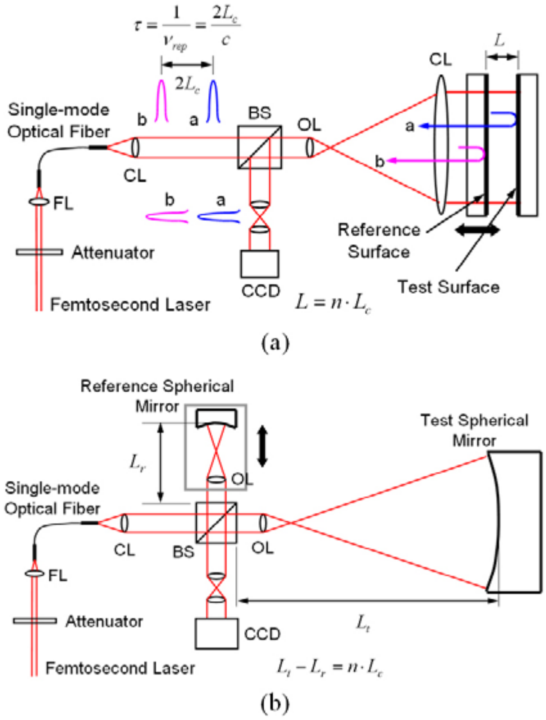

Fig. 4 Scanning interferometers using femtosecond laser pulses: (a) Unequal-path Fizeau configuration, (b) Unequal-path non-symmetric Twyman-Green configuration. Lc, cavity length; BS, beam splitter; FL, focusing lens; CL, collimating lens; OL, objective lens.

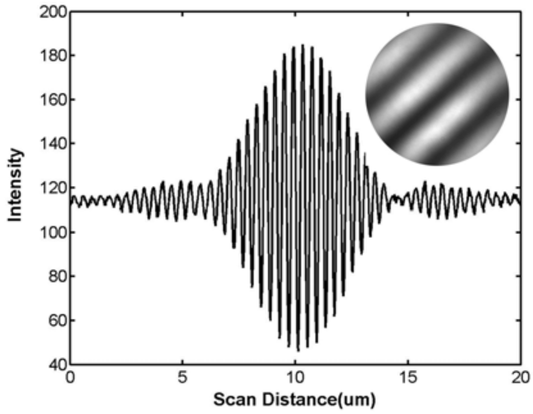

Fig. 5 A typical temporal interferogram sampled with scanning from a single pixel of the CCD camera. Inlet, a spatial interferogram captured instantaneously by using the whole pixels of the CCD camera.

3. Surface profile measurements

Use of ultrashort pulse lasers also allows one to improve the performance of the optical surface metrology that has long been dominated by CW lasers and white light. Figure 4 depicts two possibilities of using femtosecond pulse lasers as a new interferometric light source for enhanced precision surface profile metrology.11) First, a train of ultra-fast laser pulses yields repeated low temporal coherence, which allows performing unequal-path scanning interferometry that is not feasible with white light. Second, high spatial coherence of femtosecond pulse lasers enables to test large size optics in non-symmetric configurations with relatively small size reference surfaces. These two advantages are verified experimentally using Fizeau and Twyman-Green type scanning interferometers. Figure 5 shows a typical interferogram obtained using a femtosecond pulse laser while the reference arm is scanned along the optical axis by use of a fine microactuator. The unique combination of low temporal coherence with high spatial coherence provided by femtosecond pulse lasers allows performing low temporal coherence scanning interferometry with non-symmetric configurations, which is practically not feasible when using white light that is spatially incoherent. Besides, the repetitive nature of temporal coherence with a period of twice the cavity length of the ultra-fast pulse lasers enables to realize unequal-path interferometry, which is not possible by using white light. A minor problem is the appearance of diffractive rings in resulting interferograms caused by dirt coupled with high spatial coherence of the sources, but its effect may be minimized by adopting the fringe peak detection method in surface reconstruction.

4. Conclusions

New technical possibilities of adopting ultrashort femtosecond pulse lasers as a new light source for advanced optical interferometry have been described in conjunction with absolute distance measurements as well as large-scale surface profiling. To quantitatively describe the capacity of

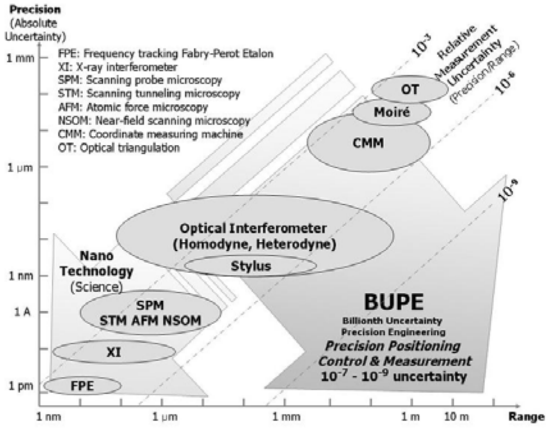

Fig 6 Billionth Uncertainty Precision Engineering - Evolutional direction of measurement technology for industrial dimensional inspection measurements. The advent of ultrashort pulse lasers as a new interferometric light source is anticipated to make many contributions to BUPE technology.

dimensional metrology for positioning and inspection measurements, the relative uncertainty may be more effectively used as compared with the absolute uncertainty, being defined by the ratio of the absolute uncertainty to the whole operating range within which ultra-precision is functional. In current precision engineering, the standard of relative uncertainty that has been realized generally is from 10^{-3} to 10^{-6} as shown in Figure 6. The range is limited because, although the precision resolution is maintained at the micrometer or nanometer level, the actual range of operation is restricted. But, in order that productions of, for example, semiconductors, optical communications components and computer parts can continue to represent the frontier industries, the standards of relatively uncertainty demanded by industry will and do exceed today's standards. Demands are already reaching a level of 10^{-7}, and it is predictable that sooner or later will extend from 10^{-8} and eventually even to 10^{-9}. In addition, we can be assured that the needs of medicine, quantum physics, biology and other fields will expand also. Thus the basic goals of precision engineering today is urgently to secure the 10^{-9} degree of relative uncertainty in order to support those strategic industries remain competitive. In this viewpoint, the advent of ultrashort pulse lasers as the new light source for the various forms of advanced interferometric measurements will make dominating contributions to the practical establishment of billionth uncertainty precision engineering.

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