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Review of surface profile measurement techniques based on optical interferometry

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ABSTRACT

With the fast development of modern science and technology, two or three-dimensional surface profile measurement techniques with high resolution and large dynamic range are urgently required. Among them, the techniques based on optical interferometry have been widely used for their good properties of non-contact, high resolution, large dynamic measurement range and well-defined traceability route to the definition of meter. A review focused on surface profile measurement techniques of optical interferometry is introduced in this paper with a detailed classification sorted by operating principles. Examples in each category are discussed and analyzed for better understanding.

1. Introduction

Product surface reflects both the external and internal characteristics of the product and measurement of surface texture is of great importance to be associated with the product application in some way. With the fast development of modern science and technology, in addition to the mechanical high precision surface, manufactured items such as micro-nano-scale sensors, nano electromechanical systems (NEMS), micro-electromechanical systems (MEMS) and precision optical components come to be used widely in machining industry, computer industry, biomedicine and other fields. This indicates that the measurement and evaluation of surface texture at micro-nano scale are becoming far more important than ever being. As a consequence, two or three-dimensional surface profile measurement with high resolution and large dynamic range is in urgent demand, and it has been attracted amount of research on this issue. Among the developed techniques, the optical interferometry based techniques have been played a leading role in the field of surface profilometry, for their good properties of non-contact, high resolution, high precision and well-defined traceability route to the definition of meter.

Reviewing a large amount of the research source we can divide the surface profile measurement techniques into two types, the optical type and the non-optical type. For the non-optical type, it could be further divided into the electrical techniques and microscope techniques. The former techniques include the resistance [1], the capacitance [2] and the inductance measurement methods [3], while the latter one include methods using transmission electron microscope (TEM), scanning electron microscope (SEM), scanning probe microscope (SPM), scanning tunneling microscope (STM), photon scanning microscope (PSM), atomic force microscope (AFM) and scanning near field optical microscope (SNOM), etc. These techniques have disadvantages of nonlinearity or small dynamic range, and thus can not meet the advanced requirement of surface profile measurement. The optical type of surface profile measurement techniques include the laser trigonometry method [4,5], the optical lever method [6], the structured light method [7–9], the confocal scanning method [10,11] and the optical interferometry [12,13]. Among these surface profile measurement techniques, the optical interferometry based techniques have gained most widespread use, not only are they non-contact measurement modes, which is important where the target surfaces are physically inaccessible or susceptible to damage when the surfaces are contacted with physical probes, but also the optical interferometry based techniques do possess high measurement resolution with relatively large measurement range [20]. Additionally, the optical interferometric techniques have the noticeable advantage of well-defined traceability route to the definition of meter, which endows the techniques with high measurement precision. For most demanding surface profile measurement where accuracy at nanometer scale or even sub-nanometer scale is required to meet the technical requirement, different new designs based on optical interferometry have been developed. Typical designs are selected to be examples in this paper.

2. Classification of surface profile measurement techniques based on optical interferometry

In general, the state-of-the-art surface profile measurement techni-

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ques based on optical interferometry could be classified with different standards. On one hand, these complex measurement techniques could be classified with the types of the interferometers used in the systems, such as Michelson interferometer [14], Fizeau interferometer [15], Linnik interferometer [16], Mirau interferometer [17], Twyman-Green interferometer [18], Fabry-Perot interferometer [19], and so on. On the other hand, all those techniques could be classified with the number of the wavelengths working in the systems, such as single-wavelength systems, double-wavelength systems and multi-wavelength systems, which possess different measurement range and can perform different measurement work. Detailed introduction about these technical systems are given with examples in the following sections.

3. Surface profile measurement techniques based on traditional optical interferometry

3.1. Single-wavelength light used surface profile optical interferometric measurement systems

Generally speaking, optical interferometric displacement measurement is commonly based on the principle- it is the comparison of a distance in space between the reference light path and the measurement light path against the known wavelength of light. This principle can be much more obviously to see in the systems of this section as the known wavelength here is the single wavelength of incident light.

For some measurement systems, typical interferometers are utilized only to measure the ultra-precise displacement so as to carry out the surface profilometry. Like the surface profile measurement of a Kirkpatrick–Baez (KB) mirror coating on a spherical Si substrate [21], researchers use traditional one-shot Fizeau interferometer to obtain the precision surface profile measurement to help to focus X-ray down to 150 nm or even smaller. Meanwhile, phase-shifting and polarization methods are common to be introduced to work with the interferometers for more accurate and efficient surface profile measurement.

He Guotian et al. proposed a sinusoidal phase modulating (SPM) interferometer to realize real-time surface profile measurement [22]. The whole setup is shown in Fig. 1, consisting of a Twyman–Green interferometer and an electrical system. After being collimated by the lens and split by the beam splitter BS, a He-Ne laser beam is split into two interference beams. One beam served as the reference beam is reflected by a sinusoidally vibrating mirror driven by a piezoelectric transducer (PZT) attached to the back to modulate phase and the other served as the measurement beam is reflected by an object. The two beams interfere to form the interference signal imaged onto a high speed image sensor based on a low speed CCD. After phase demodulated real-time by a signal processing circuit to the CCD output video signal, the phase distribution of the measured surface can be obtained, as well as the surface profile. Their experiments measuring the surface profile of a wedge-shaped optical flat show that the measurement time of this system is less than 10 ms while the repetitive measurement accuracy is 5.2 nm.

The piezoelectric transducer (PZT) is well known for obtaining phase shifting in interferometric measurement systems. It is also used by Chuen Lin Tien et al. to propose a hybrid and flexible interference microscope combined with two different phase algorithms [23] to measure the surface roughness of thin films [24]. From the structural diagram of Fig. 2 we can see that, this system comprised a modified Michelson-type interference microscope equipped with a 50 × microscope objective, a two-axis translation stage, a computer-controlled PZT translation device, and a CCD camera. A specially developed MATLAB program based on Fast Fourier Transform (FFT) and five-step phase-shifting algorithms are used to analyze the captured interference images.

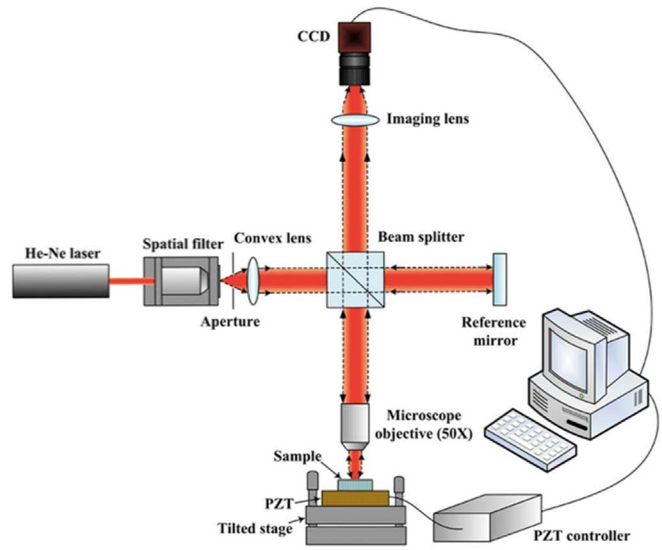

Fig. 2. Hybrid interference microscope for surface roughness measurement.

Two different types of fringe patterns are used here. One is the single-fringe pattern used for FFT method with a suitable frequency filter to obtain the phase distribution of the measured surface. The other case, for the five-frame fringe pattern, the phase difference is varied through PZT scanning introducing a subsequent phase change of 90°. The phase of the fringe is calculated using Eq. (1).

$$\varnothing(x, y) = tan^{-1}\left[\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1}\right] \tag{1}$$

where $\varnothing(x, y)$ is the phase function, I_1 to I_5 represent the digitized intensity at particular points on the five interferograms. The system has the advantage of relatively fast and low-cost for high-precision surface analysis.

High-speed phase-shifting technique has been fast developed and the measurement speed can be as high as the frame rate of the camera, allowing the measurement to be insensitive to vibration of frequency lower than that of phase stepping. Geometrical phase shifters are introduced often to take phase-shifted interferograms under high frequency vibration situations. N.R. Sivakumar et al. has done some work on non-mechanical and instantaneous phase shifting homodyne interferometry for measuring large flat surface profile in vibrating

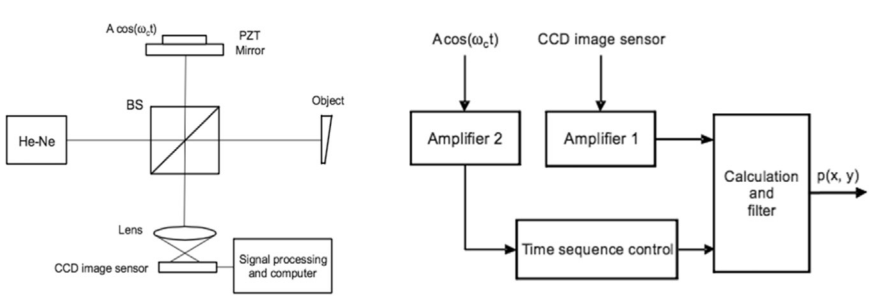

Fig. 1. Setup for real-time two-dimensional surface profile measurement.

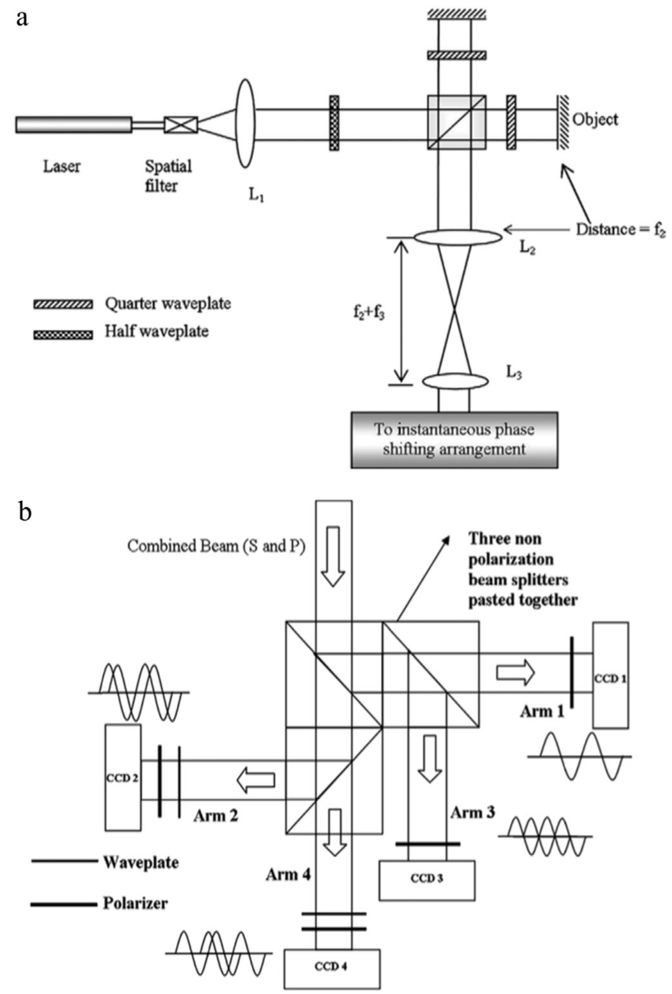

Fig. 3. (a) The homodyne interferometer of the large surface profile measurement system. (b) Instantaneous phase-shifting arrangement.

environment under 1000 Hz [25]. The homodyne interferometer of the setup is shown below (Fig. 3a).

Light from He–Ne laser source passing through a spatial filter, a collimating lens and a half wave plate is split into two orthogonally polarized beams p and s, where p-polarized beam travels straight to the object and s-polarized beam is bent 90° to the reference mirror. Both beams pass through the quarter wave plate twice respectively and are transformed back into two orthogonal linearly polarized beams, travelling in the same path towards a focusing lens and a collimating lens to the instantaneous phase shifting arrangement shown in Fig. 3b. The beam is split into four equal intensity beams by a combination of three non-polarizing beam splitters. Each of the four beams passes through a combination of quarter wave plates and polarizers to achieve the desired phase shift (0°, 90°, 180°,270°) without any ambiguity as only at the specific angles of quarter wave plates and polarizers the fringe contrast will be at the maximum.

Similarly, Zhenyue Chen et al. proposed a non-mechanical phase shift three-dimensional (3D) surface measurement method by using polarization-coded light illumination and focal plane (DoFP) polarization camera [26]. The incident light is split into left and right circularly polarized light beams to illuminate the object simultaneously. A four-channel division of the polarization camera is employed to capture the light reflected from the object surface. Four images with a phase shift of $\pi/2$ are extracted from the snap shot image and then analyzed to reconstruct a 3D object surface. It is worth of note that this system is able to measure moving objects or objects with varying shapes in high speed. More details can be known from the system experimental setup

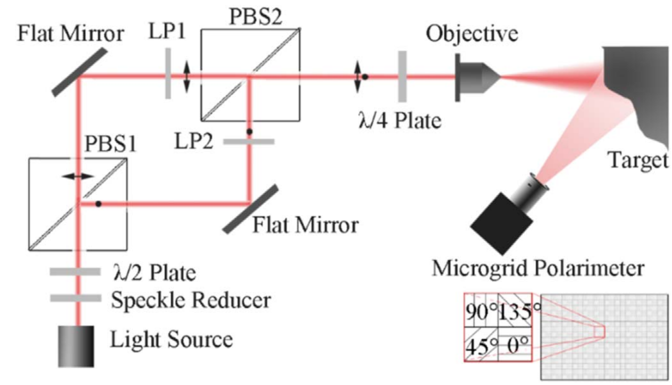

Fig. 4. Experimental setup for PBS1 and PBS2 being the first and second polarization beam splitters, LP1 and LP2 being the first and second linear polarizers.

as in the Fig. 4.

3.2. Double-wavelength light used surface profile measurement systems of optical interferometry

Interferometric optical surface profilometry using single-wavelength light source has long been used to test smooth surfaces at nanometer scale while suffering from an ambiguity of half wavelength integral multiples for the interference order of the fringes, limiting the maximum measurement range to half of the single wavelength. Double-wavelength interferometry comes to be a research hot spot to solve this for the synthetic wavelength is much larger than the single wavelength to expand the measurement range, while the accuracy of the phase measurement at the two wavelengths needs to be improved. Two main families of surface profilometry based on double-wavelength interferometric displacement measurement, the two-wavelength fringe counting interference systems [27,28] and the heterodyne systems [29], are introduced next.

The two-wavelength fringe counting interferometry is illuminating the interferometer sequentially with two wavelengths λ_1 and λ_2, to obtain the effective measurement range with an effective wavelength $\lambda_1\lambda_2/|\lambda_1 - \lambda_2|$. The alignment of the paths, the accuracy of the laser wavelengths (including refractive index effects) and the accuracy of the fringe interpolation performed, those errors do have a great impact on the two-wavelength fringe counting interferometric systems.

Kenichi Hibino et al. developed an excess fraction method with a wavelength-tuning Fizeau interferometer and a PZT phase shifting to obtain two-dimensional (2D) discontinuous surface shape measurement [27]. As shown in the Fig. 5 above, a tunable laser diode with an external cavity is used to give the synthetic wavelength for the wavelength is scanned linearly from 632 nm to 642 nm by rotating the cavity mirror. The beam is transmitted by an isolator and divided by a beam splitter into two: one beam goes to a wavelength meter and the other is incident into a single-mode fiber for the Fizeau interferometer. The measurement of the approximate distance can be described as

$$L(x, y) = \frac{\lambda_1\lambda_2}{2(\lambda_2 - \lambda_1)}(N_1 - N_2 + \varepsilon_1 - \varepsilon_2) \tag{2}$$

where the displacement L is proportional to the interference orders (integers N or fractions ε) at the two wavelengths and the synthetic wavelength $\lambda_1\lambda_2/|\lambda_1 - \lambda_2|$. The appropriate value of $(N_1 - N_2 + \varepsilon_1 - \varepsilon_2)$ could be obtained by the wavelength-tuning Fizeau interferometer with PZT phase shifters. Experiment results demonstrate that the determination of absolute interference order can give the profile of a discontinuous surface with 1 mm measurement range and 12 nm measurement accuracy.

Jonas Kühnalso used double-wavelength interferometry with digital holographic microscopy (DHM) to present a fast high-roughness non-contact surface measurement system [28]. A TR scan system is optically

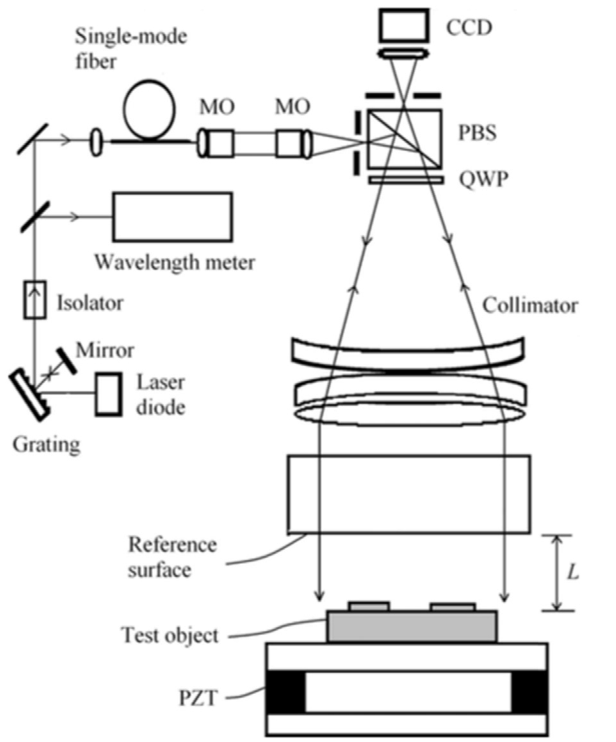

Fig. 5. Optical setup of wavelength-tuning interferometric surface measurement system.

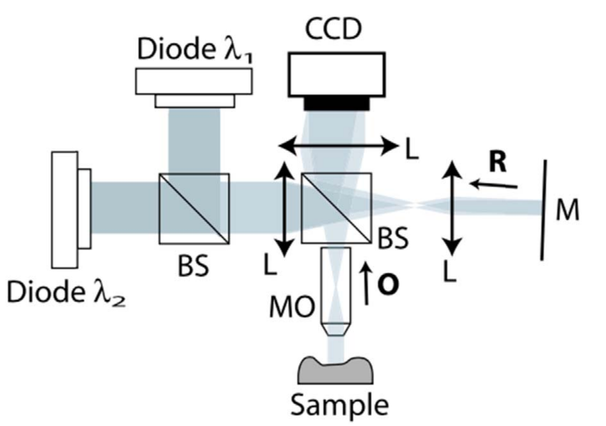

Fig. 6. Schematic of the TR scan optical setup. BS, beam splitter; L, lens; M, mirror; MO, microscope objective; O, object beam; R, reference beam.

based on a Michelson reflection DHM configuration as depicted in Fig. 6. The holograms (interferograms) of these two wavelength laser beams are recorded on the CCD camera one by one, reconstructed by a computer to retrieve the complex wave fronts, then the phase difference between the two wave fronts is computed to yield a topographic beat-wavelength map which can resolve height variations in micrometer-range. Generally, a heterodyne interferometer uses two polarized beams with slightly different frequencies achieved by either a Zeeman-stabilized laser or a single-frequency laser with an acousto-optic modulator. There would be Doppler frequency shifting of the measurement beam if the measurement arm changes its length, which leads to the frequency difference between the reference beam and measurement beam. Heterodyne interferometer systems are much used as they are insensitive to environment for AC output signal. Suat Topcu et al. proposed a method of displacement control at nanometer scale based on a heterodyne Michelson's interferometer and a homemade high frequency electronic circuit [29]. Experimental setup is detailed in Fig. 7.

The laser head is synchronized with an external reference signal from the homemade electronic circuit. Movable mirror is mounted on a

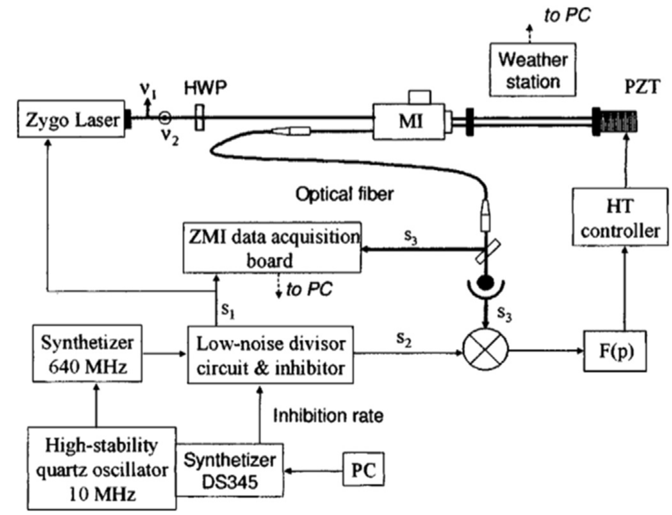

Fig. 7. Experimental setup based on a heterodyne Michelson's interferometer and a high frequency electronic circuit.

PZT actuator. The interferometer output beam is divided by a 50/50 neutral density beam splitter, sent respectively to the ZMI data acquisition system to measure the displacement value and the mixer to be compared to s_2 with quantified phase jumps. Error signal is sent to a high voltage controller to lock in the PZT and a weather station allows us to measure the fluctuations of the refractive index of air. This system is able to control the translation stage moving with a known step of 4.945 nm.

3.3. Multi-wavelength light used surface profile measurement systems of optical interferometry

Using multiple wavelengths and sequentially subtracting the phase maps can increase the ambiguity-free range to a large extent, meanwhile, white-light interferometry is becoming a state-of-the-art discontinuous surface profile measurement technique for high interference fringes occur only when the optical path difference between reference arm and measurement arm is zero. Optical interferometric surface profile measurement based on white-light interferometry [30,31], spectrally resolved white-light interferometry (SRWLI) [32–34], Fabry-Perot interferometry [35] and narrowly defined multi-wavelength interferometry [36] will be discussed in this section.

Taeyong Jo et al. combined white-light scanning interferometry with reflectometry to measure the thin-film thickness and surface profile separately [30] (See Fig. 8). A vertical movement in the z direction is implemented using a PZT actuator toward the test surface located in the x-y plane. The light source is a halogen lamp with broad and continuous spectrum. When the setup is under the reflectometry mode, the normal objective lens and spectrometer are used to obtain the thickness of the specimen by recording the interference between the top and bottom surface of it. When under interferometry mode, the interferometric objective and CCD camera are used to record the interference signal between the test and reference surface. In this mode, the interferogram gives information about the absolute thin film thickness and surface profile simultaneously.

Wang Shenghui et al. also built up a vertical scanning white-light interference stitching measurement system that can reduce the stitching data amount and expand the horizontal measuring range [31]. Although white-light interferometry has gained widespread use in ultra-precision displacement for having no problem of phase ambiguity, it requires a large number of optical path difference (OPD) scanning, which could introduce environmental noise. Another method known as the spectrally resolved white-light interferometry (SRWLI) does not have this problem. The interferogram here can be considered as a

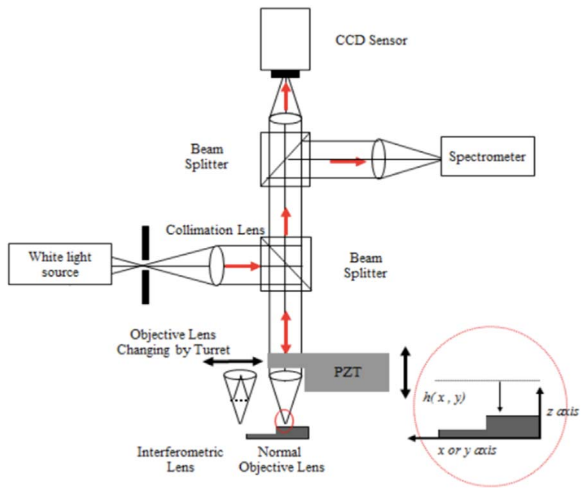

Fig. 8. The combined surface profile measurement setup.

superposition of monochromatic interferograms under different wavelengths and can be separated with the help of a grating or dispersive prism. By calculating the phase slope with respect to the variation of the wavenumber, the OPD of one line profile can be obtained without scan process.

Pei Zhu et al. presented a two-dimensional (2D) SRWLI system combined with a Fabry–Perot (F-P) etalon and a Mirau interference microscope objective to measure a narrow rectangle profile with only one frame of interferogram [32]. Fig. 9 shows the experimental setup for the measurement. The well collimated incident white light go through the F-P etalon vertically to produce the filtered frequency comb entering into the Mirau interference microscope objective. The interference pattern of beams reflected from reference surface and test surface is imaged onto the adjustable slit through which the size of the test area can be controlled. A blazed grating is used to disperse the overlapped monochromatic sub-interferograms and by making sure the sub-interferograms of adjacent wavelength don't overlap each other, a 2D surface profile can be obtained. The test area is only 20 µm wide in this paper but larger test area can be measured by enlarging the wavelength interval of the frequency comb.

Apart from FP etalon, acousto-optic tunable filter has also been used

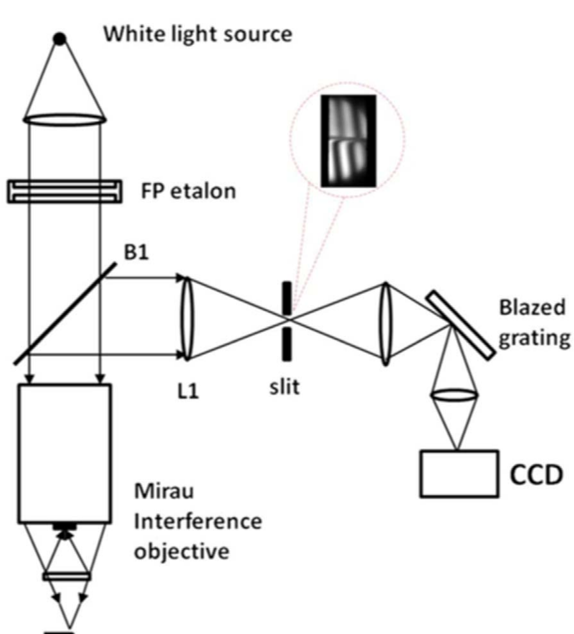

Fig. 9. Experimental setup of 2D SRWLI system.

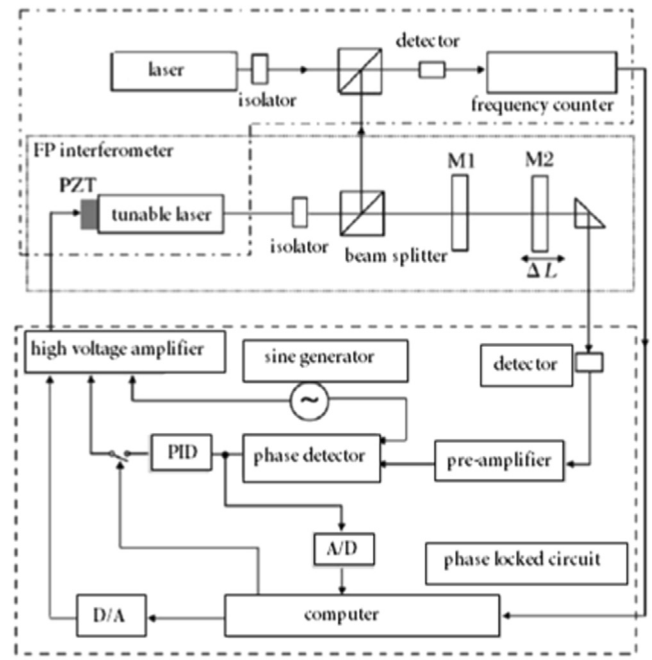

Fig. 10. The displacement measurement system based on a Fabry-Perot interferometer.

commonly in SRWLI interferometry to generate a sequence of light wavelengths. Feng Gao et al. used a halogen light source with an acousto-optic tunable filter to produce wavelength scanning for a Linnik interferometer [33]. Daesuk Kimalso used acousto-optic tunable filter for equally spaced 5 spectral phase shifting in the 3D micro surface profile measurement system based on a Michelson interferometer [34].

As we all know, Fabry-Perot interferometry has super high resolution reaching to picometer scale in theory for high contrast and sharp shape of its interference fringe. Although facing a lot of technique problems when used in practical, Fabry-Perot interferometer based surface measurement is still common to see in different systems. Duan Xiaoyan et al. proposed a micro-displacement measurement system based on a Fabry-Perot interferometer for the frequency of the Fabry-Perot interferometer changes with the displacement of the measurement mirror, as well as the frequency of the tunable laser [35]. The principle diagram of the system is shown above in Fig. 10 and the measurement mirror displacement ΔL can be obtained by Eq. (3).

$$\Delta L = -\frac{\Delta f}{f}L \tag{3}$$

where L is the original cavity length of the Fabry-Perot interferometer, f is the original resonant frequency, Δf is the frequency change of the tunable laser source. By measuring the frequency change rather than the displacement change, the system resolution can be improved greatly. And it also avoids the errors caused by interference fringe subdivision in conventional double-wavelength interferometry.

Narrowly defined multi-wavelength interferometry refers to those using several different wavelength laser sources not coming from white light to unwrap the phase map and obtain the surface measurement.

Like Minah Choi et al. did in precision large-stepped surface profile measurement, she used a frequency comb of a femtosecond pulse laser to select out four optical wavelengths for multi-wavelength interferometry with traceability to the Rb atomic clock of time/frequency standard [36]. From the system layout shown above (Fig. 11), a 4xl fiber switch is used to route the phase-locked four DFB lasers one at a time to the Twyman-Green interferometer through a second harmonic generation (SHG) crystal. The reference mirror is translated by PZT for phase shifting along the optical axis. Since the comb-based method can

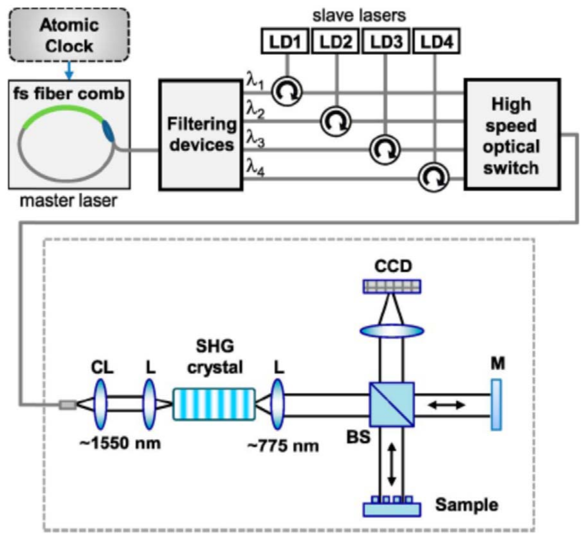

Fig. 11. Schematic of the frequency comb used multi-wavelength interferometric surface measurement.

provide any desired set of wavelengths within the femtosecond laser spectral bandwidth, the non-ambiguous measurement range can be largely extended to tens of millimeters with carefully selection of the four wavelengths. Paul Kumar Upputuri also proposed a three-wavelength interferometric 3D surface profile measurement method by the fact that variation of phase with wavenumber is linear to the absolute profile height [37].

4. Surface profilometry using ultra-precise displacement measurement based on other kinds of interferometry

Compared to the traditional optical interferometric surface profile measurement, systems in this section have special working structures based on X-ray interferometry and optical feedback interferometry.

4.1. X-ray interferometry based surface profile measurement systems

In the mid-1960 s an interferometric technique based on X-rays was first proposed and soon developed to be an angstrom-scale ruler for length measurement. The X-ray interferometer provides with subdivision of optical fringes for each X-ray fringe corresponds to a displacement equaling to the lattice parameter of silicon, *ca.* 0.19 nm for the (220) lattice planes. G. Basile developed an instrument referred to as combined optical and X-ray interferometer (COXI) in which the X-ray interferometer is employed to subdivide optical fringes down to sub-nanometer levels to avoid the errors often associated with electronic subdivision [38]. Further details can be seen in Fig. 12.

The essential components of the X-ray interferometer are the three lamellae that serve as the beam-splitter, the beam-combiner and fringe analyzer respectively, forming a Mach-Zehnder interferometer for X-rays by diffraction at the lamellae. The optical interferometer is a two-beam interferometer in which the two beams have orthogonal linear polarization states. A Pockels cell at the entrance of the interferometer introduces a time-modulated phase shift between the two states. The output of the optical interferometer is detected synchronously with respect to the modulating frequency of the Pockels cell using a phase-sensitive detector. The optical interferometer measures the whole number of optical fringes while the X-ray interferometer measures the fractional part of the fringe.

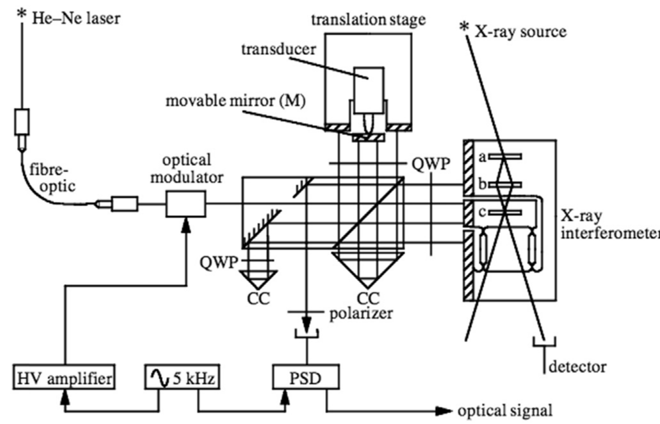

Fig. 12. Combined optical and X-ray interferometer system.

4.2. Optical feedback interferometry based surface profile measurement systems

Optical feedback interferometry (OFI) which is also called the self-mixing interferometry (SMI) occurs in a laser diode (LD) when a portion of light emitted from the LD is reflected by an object and coupled into the LD cavity. The reflected light carrying some information of the external target mixes with the original light in the LD cavity and changes the output power and spectra of the laser [39–43]. Francisco J. Azcona et al. proposed a differential optical feedback interferometry (DOFI) based method to measure nanometric displacement [44]. Here is the setup diagram in Fig. 13.

DOFI is a technique of comparing two OFI signals subjected to a known reference motion. A reference laser is placed pointing to a stable linear motion device, and the measurement laser attached to the motion stage, aims to the measurement target. In the case of a static target, and considering that both lasers are capable of emitting the same wavelength, both OFI signals would have the same number of transitions for any reference displacement of amplitude. Also time intervals between transitions in both signals should be equal during the same part of the reference motion. If the target moves along the measuring direction, a small time variation between the intervals produced in the reference and measurement signals will be detected, so as to estimate the amplitude and sense of the target motion with very high resolution by using the time difference. Experiment results show that experimentally it is possible to measure displacement with resolution of $\lambda/100$. Surface profile measurement with resolution at this scale can be obtained based on this method.

5. Conclusion

Optical interferometry based surface profile measurement techniques have gained widespread use for their good properties of non-contact, high resolution, large dynamic measurement range and well-defined traceability route to the definition of meter. A review focused on surface profile interferometric measurement techniques is intro-

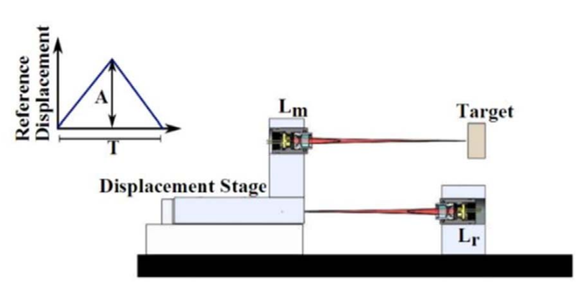

Fig. 13. Setup of DOFI.

duced in this paper with a detailed classification. Systems belonging to the traditional optical interferometry group can be further organized as single-wavelength light, double-wavelength light and multi-wavelength light used systems. For the first type, typical interferometers are sometimes utilized only or with phase-shifting, polarization methods to proceed the profilometry. To expand the measurement range, double-wavelength interferometry comes to be a research hot spot and two-wavelength fringe counting interference systems and heterodyne systems are introduced with examples. Since using multiple wavelengths can increase more ambiguity-free range, surface profile measurement systems based on white-light interferometry, spectrally resolved white-light interferometry (SRWLI), Fabry-Perot interferometry and narrowly defined multi-wavelength interferometry have been developed at a fast speed. Compared to the traditional ones, other optical interferometric surface profile measurement systems are based on different working structures like X-ray interferometry and optical feedback interferometry. The X-ray interferometer can provide with subdivision of optical fringes down to sub-nanometer levels without errors associated with electronic subdivision. In the case of OFI displacement measurements, researchers have proposed methods to increase the maximum attainable resolution up to $\lambda/1000$, with very simple structure. For the most demanding surface profile measurement where accuracy at the nanometer level or sub-nanometer level is needed, new designs based on ultra-precise displacement measurement techniques of optical interferometry are being the focus in research and developed increasingly.

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