Measurement technology based on laser internal/external cavity tuning

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ABSTRACT

For an ordinary laser with two cavity mirrors, if the length of laser cavity changes half wavelength the laser frequency changes one longitudinal mode separation. For a laser with three cavity mirrors, in which a feedback mirror is used to feed part of the laser output beam back into the laser cavity, the external cavity length changes half wavelength the laser intensity fluctuates one period. This presentation gives some research results in measurement field based on changing (tuning) the length of laser internal/external cavity, including 1) HeNe laser cavity-tuning nanometer displacement measurement instruments (laser nanometer rulers), 2) HeNe laser feedback displacement measurement, 3) Nd:YAG laser feedback nanometer displacement measurement, 4) benchmark of waveplate phase retardation measurement based on laser frequency splitting, 5) in-site waveplate phase retardation measurement instruments based on laser feedback and polarization hopping, 6) quasi-common-path microchip Nd:YAG laser feedback interferometer, 7) non-contact Nd:YAG laser feedback surface profile measurement. Some of these instruments have been put into application and display some irreplaceable advantages.

Keywords: HeNe lasers, Nd:YAG lasers, cavity tuning, laser feedback effect, displacement measurement, phase retardation measurement, surface profile measurement.

1. INRRODUCTION

In this presentation, there are three basic concepts on laser which are the foundation of the measurement technology introduced here.

Laser frequency splitting [1]

One frequency of the laser will be split into two frequencies by a birefringence elements quartz crystal or a forced element or an electro-optical crystal loaded by voltage in the laser cavity. The frequency difference between two frequencies is proportional to the phase retardation of birefringence elements and their polarizations are orthogonal to each other. The “Birefringence dual frequency laser” comes from this “Frequency splitting technology”.

Laser internal cavity tuning

There are two cavity mirrors in an ordinary laser. We use a PZT to pull/push one of the two mirrors to give a few half-wavelength displacements and detect the laser power or intensity variation. The displacement of the mirror changes the laser cavity length, which is called “Laser internal cavity tuning”. The term “internal” means inside the laser.

Laser feedback associate with external cavity tuning

To add an extra mirror to reflect part of the laser beam back into the laser itself is called laser feedback. The additional mirror associates the nearest laser mirror to construct a new cavity. The new cavity is called “Laser external cavity”, which can be tuned by a PZT.

Laser cavity tuning characteristics have great potential for measurements. The laser gyro with three cavity mirrors is a successful sample, which transforms rotation angles of aircrafts and ships into frequency differences of the laser. In a standing-wave laser with two cavity mirrors in general, while the cavity mirror moves a micrometer, the laser frequency will shift a few GHz. This brings us ideas of conducting high-resolution measurements with the efficient transform.

Along this way, researches have achieved big advancements. This presentation summarizes such research results in my group at Tsinghua University, which have shown a wide application prospect.

Discoveries on the laser cavity tuning are directly applied as principles of measurement in our group and then usable instruments are made. These achievements are as follows.

(1) Laser nanometer ruler [2]
(2) Displacement sensor based on the feedback of HeNe dual frequency lasers [3]

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(3) Compact displacement sensor based on the birefringent external cavity feedback of microchip Nd:YAG lasers [4, 5]
(4) Waveplate phase retardation measurement instrument based on frequency splitting [6,7]
(5) Waveplate phase retardation measurement instrument based on optical feedback [8]
(6) Quasi-common-path Nd:YAG laser feedback interferometer [9]
(7) Nd:YAG laser feedback confocal frofilometry

2. LASER NANOMETER RULER

Along with the continuously tuning of one laser cavity mirror, the output intensity of laser varies periodically. By splitting a longitudinal mode into two modes, four states of combination in polarization are formed in the output of the laser, i.e. a single o-light, both o-light and e-light, a single e-light, and no light, and these repeat. The output state shifts once as the mirror moves by a length of 1/8 wavelength and completes a cycle after the mirror moves a length of four 1/8 wavelengths, i.e. 1/2 wavelength. As seen in Fig.1, an apparatus for displacement measurement based on this principle is constructed. The laser, without the need of being frequency stabilized, can be deemed as operating in its central frequency and being traceable to the optical wavelength due to its self-calibration, i.e. passing by the central frequency for each movement of 1/2 wavelength.

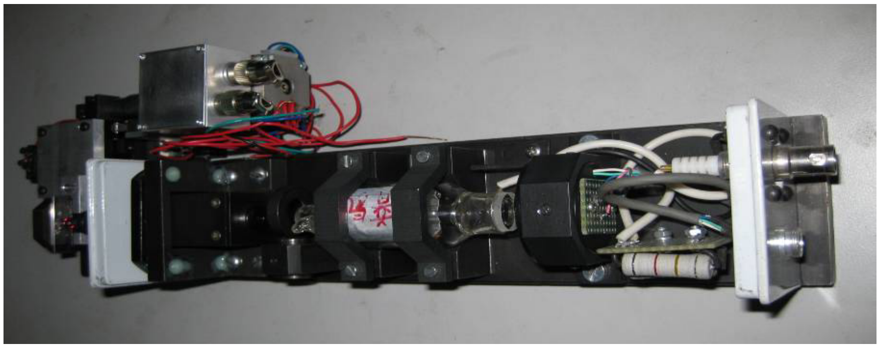

Fig.1 Laser nanometer ruler prototype

The apparatus with 633nm wavelength has a measurement range of 12mm, a resolving power of 79nm, a standard deviation of 0.2μm, a linearity of 0.005% and a zero drift of 0.16μm/hour. The nano-scale in operation presents high resistance to disturbance and better stability over laser interferometers.
Currently, a similar apparatus with 1152nm wavelength has been constructed, which has a measurement range of 100mm, a resolving power of 20nm.

3. HENE LASER FEEDBACK DISPLACEMENT SENSOR

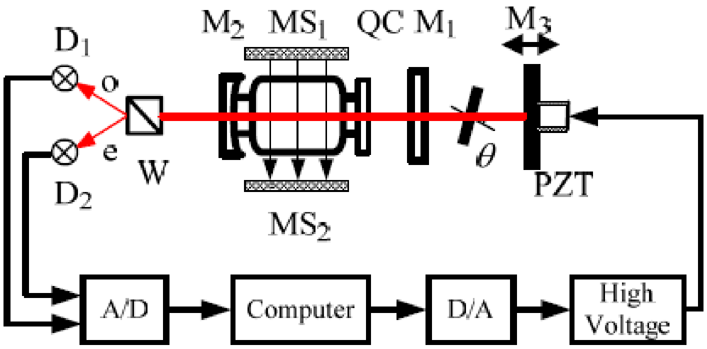

Fig.2 M1, M2: mirrors; MS1, MS2: magnet strips; QC: quartz crystal; M3:external feedback mirror with high reflectivity; PZT: piezoelectric transducer; W: Wollaston prism; D1, D2: detectors

As shown in Fig.2, Zhang and his colleagues have developed a displacement meter using strong optical feedback from a highly reflective mirror into Zeeman-Birefringence lasers. Like the laser nanometer ruler, the state of polarization weaves of the laser in feedback (which may be only o-light; both o-light and e-light; only e-light; and then no light) shifts sequentially as the feedback mirror moves along the axis of the laser, and the time interval of the polarization shift corresponds to a displacement of the feedback mirror by 1/8 wavelength. It is easy to distinguish direction and subdivide half-wavelengths in this system.

Unlike the laser nanometer ruler, in which the laser cavity varies in length, this apparatus has a fixed cavity length and hence a larger measurable range up to 50 mm or more.

4. ND:YAG LASER FEEDBACK DISPLACEMENT SENSOR

Fig.3 is the schematic diagram of a microchip Nd:YAG laser feedback system with birefringence external cavity. Tan and Zhang proposed such a novel laser feedback scheme, called external birefringence feedback. A waveplate is inserted in the external cavity, two in-quadrature polarized laser intensity signals with a certain phase difference can be obtained as the feedback mirror moves along the axis of the laser. If the phase retardation of the wave plate $\delta=45^0$, a phase difference about 90^0 exists between the two in-quadrature laser intensities, stable and independent of the variation of the external cavity length, which are similar to signals in general laser interferometers.

Based on the principle discussed above, a compact Nd:YAG laser feedback displacement sensor is designed. The displacement is got from the integer of $\lambda/2$ and the fraction phase caused by the displacement. The resolution of the system is up to 15nm and measurement range up to 100mm or more.

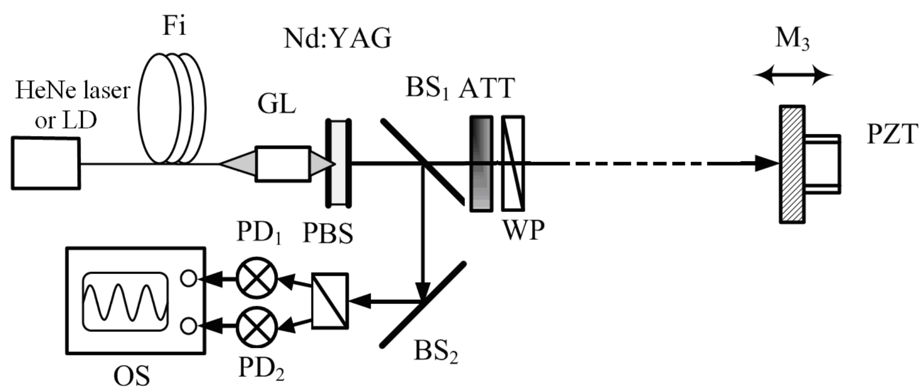

Fig.3 Schematic diagram of microchip Nd:YAG laser feedback with birefringence external cavity. Fi: optical fiber, GL: GRIN lens, ATT: attenuator, WP: wave plate, M3: feedback mirror, BS1,2: beam splitter, PBS: polarized beam splitter

5. FREQUENCY-SPLITTING WAVE PLATE RETARDATION MEASUREMENT SYSTEM

The wave plate, which is widely used in optical systems, for instance, optical interferometers, optical desks, optical communications, etc., for transforming circularly polarized lights into linearly polarized lights or reversely.

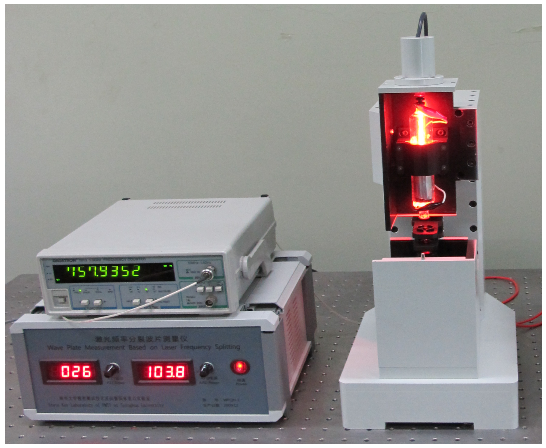

Fig.4 Frequency-splitting wave plate measurement system

The frequency difference between two frequencies by frequency splitting is proportional to the phase retardation of birefringence elements in the laser cavity. This is the principle of phase retardation measurement of wave plate. The instrument is shown in Fig.4. The formulae can be written as

$$\phi = \frac{\Delta v}{\Delta v + \Delta v'} \times \pi \quad , \tag{1}$$

$$\Delta = \Delta v + \Delta v' \tag{2}$$

Where Δ is the longitudinal mode spacing, $\Delta\nu$ is the frequency difference.

Based on this principle presented above, Zhang and his colleagues developed an apparatus for measuring retardations of wave-plates utilizing laser frequency splitting, which is capable of obtaining the retardation of a wave-plate by simply putting the wave-plate in a laser and measuring the frequency difference outputted from the laser. This technique is advantageous for its high precision up to 3 arc-min and traceability to a natural reference, i.e. the optical wavelength. It may also function as a benchmark for measurement of wave-plates, which was absent in the past.

6. LASER FEEDBACK WAVE PLATE RETARDATION MEASUREMENT SYSTEM

With a birefringence element in the external feedback cavity, our experiments shows: one period of intensity modulation includes two polarization components that oscillate alternatively; different phase differences of birefringence element make the two polarization components have different duty cycles in an intensity modulation period. The relationships of duty cycles and phase differences are nearly linear. Therefore the polarization flipping position B changes with the variation of external cavity birefringence, as shown in Fig.6.

Fei et al then developed an apparatus for measuring the retardation of wave plates based on the fact that in the case of laser feedback, the duty cycle of two orthogonal polarizations within a cycle of intensity modulation is proportional to the retardation of a wave plate under test.

This novel apparatus developed is capable of performing on-line, simple and fast measurement of wave-plates' retardation with accuracy up to 0.1 degree. Moreover, an apparatus is currently being developed for in situ measurement of wave plates on a Φ360 mm optical agglutination disk.

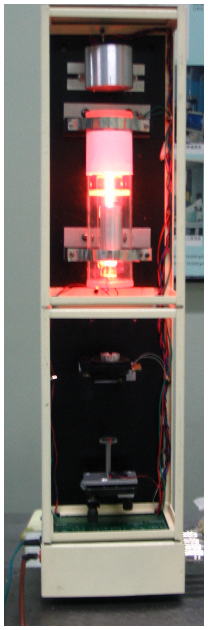

Fig.5 Laser feedback wave plate measurement system

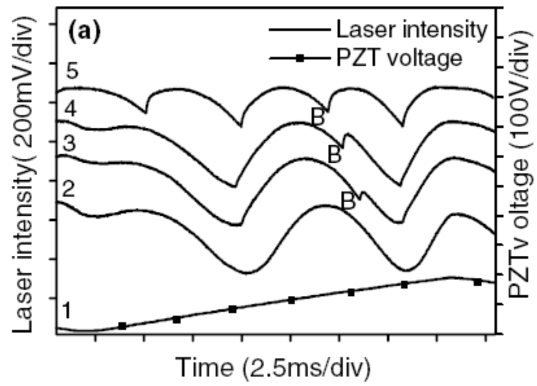

Fig.6 Laser polarization flipping for different phase retardations of birefringence in external cavity

7. QUASI-COMMON-PATH ND:YAG LASER FEEDBACK NTERFEROMETER

Based on microchip Nd:YAG laser feedback, a quasi-common-path Nd:YAG laser feedback interferometer with 1.06 μm wavelength is shown in Fig.7. The laser beam is reflected by the measurement target with displacement. The instrument combines frequency shifting and multiplexing to realize a high-resolution, high-sensitivity and environmentally robust phase measuring system.

The system employs the quasi-common-path to eliminate the air influence of interferometer, and heterodyne for measurement optical path. A frequency stabilization system is used to stable the Nd:YAG thickness to hold the frequency of the laser.

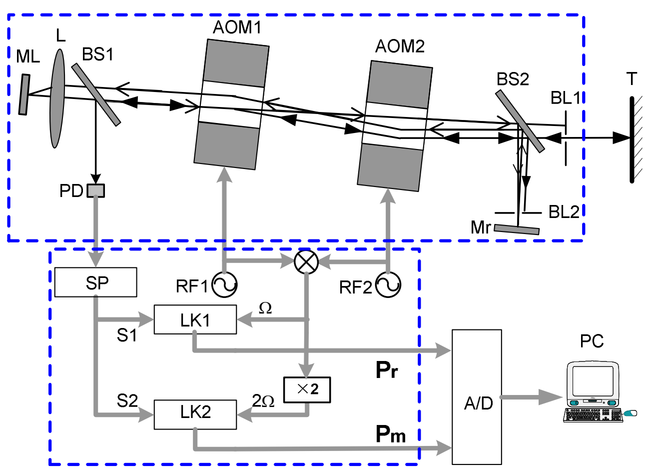

Fig.7. quasi-common-path microchip laser feedback interferometer

Compared with traditional laser interferometers, this quasi-common-path microchip laser feedback interferometer can work even when the target reflectivity is as low as 10^{-9}, which means that the instrument is quite appropriate for the non-cooperative displacement measurement of any kind of targets, including liquid surfaces. Its resolution is up to 1nm and range more than 1m.

8. LASER CONFOCAL FEEDBACK PROFILOMETRY

As shown in Fig.8, a novel profiling method, Laser Confocal Feedback Profilometery (LCFP), combining quasi-common-path heterodyne phase detection with laser confocal feedback technology, is proposed and studied.
In fact the Profilometery is a development of the quasi-common-path Nd:YAG microchip laser feedback interferometer discussed above. The microchip Nd:YAG laser emits 1064nm laser, which passes through a

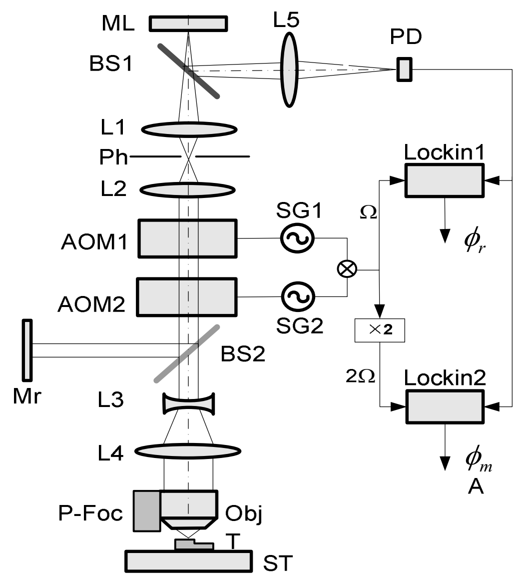

Fig.8. LCFP experimental setup

ML: microchip laser; BS1,2: beam splitter; PH: pinhole; L1-5: lens; AOM1,2: Acousto-optic modulators; Mr: reference reflecting mirror; Obj: objective; PI-FOC: objective scanner; T: target; ST: scanning stage; SG1,2: rf frequency generator; Lockin 1, 2: lock-in amplifiers. PD: photo diode.

pinhole and frequency shifter, and is focused onto the sample surface. The reflected light is coupled back to the microchip laser cavity and forms the frequency shifted feedback light, causing the laser intensity modulation. When the sample is scanned laterally, its surface height variation changes both the phase and strength of the feedback light. LCFP then extracts both the amplitude and phase information out of the laser intensity modulation to determine the integral and fractional number of half laser wavelengths contained in the height variation of two points on the sample surface. LCFP can thus overcome the half-laser-wavelength limit of phase measurement in the axial direction. The high sensitivity of microchip laser to feedback light makes LCFP able to measure samples with very low reflectivity. The LCFP experimental setup is built, and it has successfully measured the height of the stages on a glass-substrate grating, as shown in Fig.9. The current performances of LCFP are as followed: the axial resolution is better than 2nm, the axial range about 5μm, and the detectable reflectivity as low as 10^{-9}. Due to its direct traceability to laser wavelength, LCFP can potentially be used as the metrology standard of small-scale features.

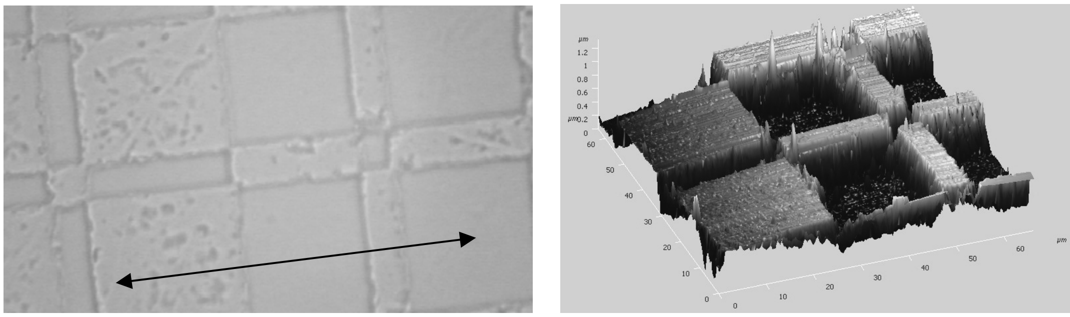

Fig.9. 2-D and 3-D image of the sample. (The line indicates the line-scanned area)

In conclusion, our study has proved that measurement technology based on the laser cavity tuning of no matter internal cavity or external cavity can be widely used in many fields. The stability and performances of these instruments are beyond the imagination we had before. Till now, most of the queries are often like that:

(1) Would the laser keep oscillating when you are tuning the laser cavity?
(2) Would the laser keep oscillating when you insert an optical element into the laser cavity?
(3) Could the laser feedback interferometer be developed into nanometer measurement instruments?

Our research results convince us with a positive answer: "Yes". We have no doubt that these instruments will be used worldwide.

9. ACKNOWLEDGEMENTS

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