Non-contact angle measurement based on parallel multiplex laser feedback interferometry*

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We present a novel precise angle measurement scheme based on parallel multiplex laser feedback interferometry (PLFI), which outputs two parallel laser beams and thus their displacement difference reflects the angle variation of the target. Due to its ultrahigh sensitivity to the feedback light, PLFI realizes the direct non-contact measurement of non-cooperative targets. Experimental results show that PLFI has an accuracy of 8″ within a range of 1400″. The yaw of a guide is also measured and the experimental results agree with those of the dual-frequency laser interferometer Agilent 5529A.

Keywords: laser feedback, angle measurement, non-cooperative targets

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1. Introduction

Currently, the optical precise angle measurement methods mainly include autocollimation,[1,2] laser interferometry,[3,4] circular grating,[5] total internal reflection,[6] etc. Autocollimator and laser interferometry have high resolution and high accuracy but usually need a mirror or a cube corner prism to reflect enough light. An autocollimator can also measure some transparent or rough targets but the measurement range decreases greatly. Circular grating usually has a large measurement range but it needs to be installed on the target and it is difficult to make high accurate gratings. Total internal reflection has a high resolution but a small range. Ren developed a roll angle measurement method based on the external-cavity birefringence feedback effects of a microchip Nd:YAG laser.[7] However, it can only measure the roll angle. These methods have their advantages and disadvantages and are used in different situations. So far there is no specific definition of non-cooperative targets. In this paper, we name targets whose angle cannot be measured directly by a laser interferometer (Agilent 5529A for example) as the non-cooperative targets, such as black, transparent, soft, liquid, small, and rough targets. Thus the non-cooperative targets are more common than the cooperative targets and the measurement of their angles is more difficult but very necessary.

Besides high resolution and high accuracy, laser feedback interferometry based on a microchip laser also has an ultrahigh sensitivity, which can realize the non-contact displacement measurement of the non-cooperative targets. It uses the principle of frequency-shifted laser feedback and heterodyne phase demodulation.[8] It still works even when the relative feedback power is as low as 10^{-13} (-130 dB).[9] Due to this advantage, there has been a lot of research on laser optical feedback imaging,[10,11] laser Doppler velocimetry,[12,13] vibrometry,[14,15] precise displacement measurements,[8,16,17] etc. The angle measurement can also be realized with a laser diode using the coherent collapse regime.[18] However, this method only works under the strong feedback situation and needs a mirror attached on the target to reflect enough light. In this paper, we present a novel parallel multiplex laser feedback interferometry (PLFI), which outputs two parallel laser beams. Displacements of two positions on the target are measured at the same time, thus the displacement difference reflects the angle variation of the target. Due to the ultrahigh sensitivity of the feedback light, PLFI can directly measure the angle variation of the non-cooperative targets.

2. System configuration

The system configuration is shown in Fig. 1. The 808-nm pump beam is divided into two by a fiber splitter. There are gradient index (GRIN) lenses at the ends of the fiber heads and they are parallel to each other with a distance D of 2.8 mm. The two pump laser beams are focused in the middle of an Nd:YAG microchip, whose diameter is 5 mm and thickness is 1 mm. The two sides of the microchip are coated with high-reflection films as the cavity mirrors. The Nd:YAG outputs two parallel laser beams. Since they are generated by the same flat-flat cavity, the two beams are both fundamental transverse modes and single longitudinal modes. Their relaxation oscillation frequencies ω_R are about 300 kHz. Two acousto-optic modulators (AOMs) are used in series to shift the frequencies of the feedback lights. AOM1 is driven by a radio-frequency (rf) signal generator (RF1) at 70.0 MHz, and AOM2 is driven

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by RF2 at 70.0 MHz $+\Omega$, with Ω being an adjustable value. The apertures of the two AOMs are large enough compared to the distance of the two laser beams so that the two beams can pass through together. When the two laser beams, labeled B1 and B2, impinge on AOM1 at the Bragg incidence angle, the -1-order diffracted beams are generated. The distance between the two AOMs is kept short enough to ensure that both B1 and B2 pass through the aperture of AOM2. After AOM2, the $+1$-order diffracted beams of B1 and B2 are generated. So the total shifted frequency is Ω. All beams other than B1 and B2 are blocked.

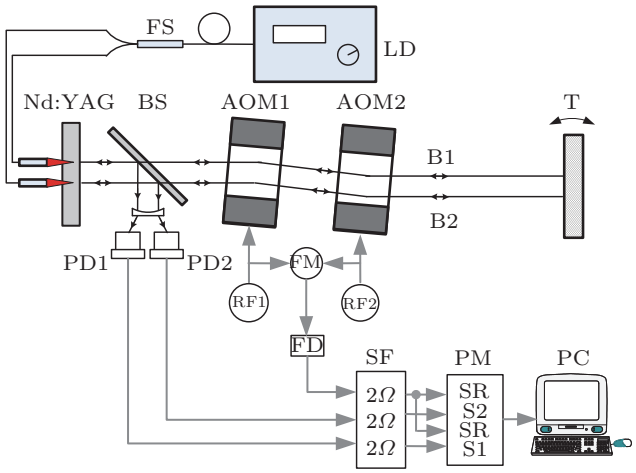


Fig. 1. (color online) Configuration of the parallel multiplex LFI. LD: laser diode, FS: fiber splitter, BS: beam splitter, AOM1, AOM2: acousto-optic modulators, M: reference mirror, T: target under test, PD1, PD2: photodiodes, RF1, RF2: drive of AOM, FM: frequency mixer, FD: frequency multiplier, SF: three-channel signal filter and amplifier, PM: phase meter, PC: personal computer.

B1 and B2 impinge on two different positions of the target and part of the reflected or diffused lights are collimated back into their corresponding laser cavities along their corresponding in-coming paths. Due to their round trips through the AOMs, B1 and B2 have a final frequency shift of 2Ω. The two feedback lights induce two 2Ω-frequency laser intensity modulations ΔI_i[8]

$$\Delta I_i = G(2\Omega)K_i\cos(2\Omega t + P_i + \varphi_i), \quad i = 1,2, \tag{1}$$

where K_i denotes the corresponding feedback light strength, P_i is the corresponding phase, and φ_i is a corresponding fixed phase shift. The frequency-dependent amplification coefficient $G(x)$ reaches its maximum when x approaches ω_R, resulting in the ultrahigh sensitivity of LFI.[8]

The modulated signals S1 and S2 are detected by two photodiodes, respectively, and extracted by filters with center frequency 2Ω. In our experiment, Ω is set at 40 kHz, which is not too close and not too far from ω_R, so $G(2\Omega)$ offers a moderate amplification to the feedback lights, avoiding the nonlinear effect and chaos. Figure 2(a) shows the intensity modulations of B1 and B2 after the filter and the amplifier in the time domain. Figures 2(b) and 2(c) show their power spectra, which have the same signal peak at 80 kHz (2Ω). Their signal-to-noise ratios are both higher than 40 dB, which are adequate for the phase meter.

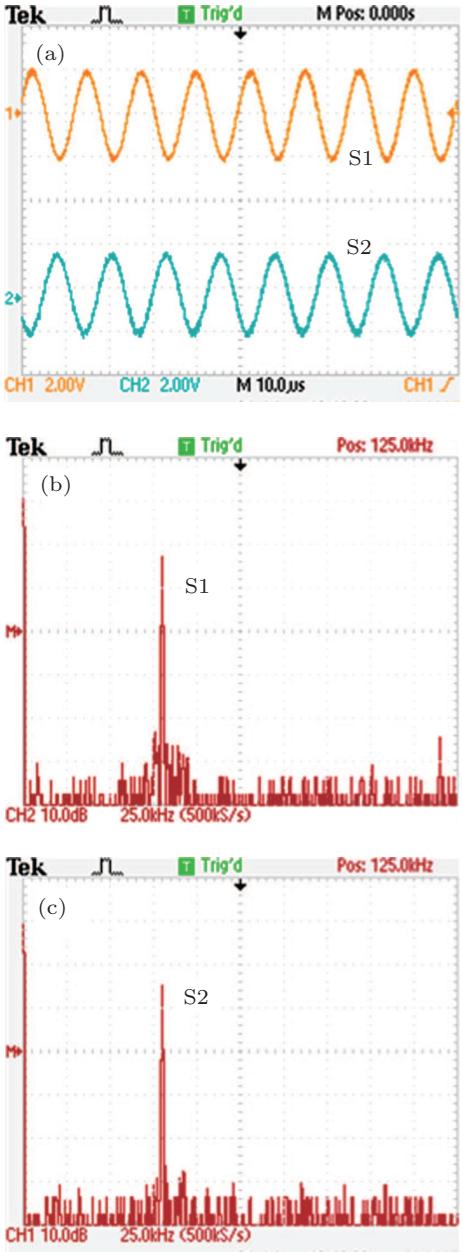


Fig. 2. (color online) Feedback signals in (a) the time domain and (b), (c) the frequency domain.

The phase variations of the two beams are detected by a two-pair phase meter (PT1313B) at the same time through a heterodyne phase measurement. A stable 2Ω-frequency sinusoidal signal SR is generated with RF1 and RF2 as a standard reference signal. By sending SR and S1 into the first pair of channels of the phase meter, the phase variation of B1 named ΔP_1 is precisely measured. Similarly, the phase variation of B2 named ΔP_2 is measured by sending SR and S2 into the other pair of channels of the phase meter. The ΔP_1 reflects the displacement of position I of the target, while ΔP_2 reflects the

displacement of position II of the target, and their subtraction reflects the angle variation of the target.

The target displacement difference ΔL is related to the feedback light phase variation ΔP ($\Delta P = \Delta P_1 - \Delta P_2$)[8]

$$\Delta L = (c/2n\omega)\Delta P, \tag{2}$$

where n is the refractive index of the air, ω is the angular frequency of the laser, and c is the light velocity in a vacuum.

The target angle variation θ (when θ is small) can be expressed as

$$\theta \approx \tan\theta \approx \frac{\Delta L}{D}, \tag{3}$$

where D is the distance between the two laser beams.

The displacement resolution of the laser feedback interferometer is claimed to be 1.8 nm according to Wan's letter.[8] Thus the theoretical angle resolution is 1.8 nm/$D \approx 0.1''$. The resolution can be further improved by increasing D.

This scheme does not generate any signal crosstalk. On one hand, only when the laser beams go back exactly along the same paths as they come to the target on can their frequencies be shifted by 2Ω and demodulated by the heterodyne phase measurement. On the other hand, as we know, a minor difference between the cavity lengths can cause a large laser frequency difference. Although the two beams are generated from the same microchip, their frequencies have a big difference since their cavity lengths are not exactly the same, so they cannot interfere with each other. They will form a beat whose frequency is high (about several GHz) and the beat can be filtered out by the low frequency filters in our signal processing unit. Another advantage of this scheme is that the optical paths of B1 and B2 are very close to each other, the environmental disturbance is nearly the same for them. So their subtraction can eliminate the environmental disturbance and thus accurately reflect the angle variation. Because there are two laser beams, B1 and B2, working simultaneously and the laser beams are parallel, we call this scheme the parallel multiplex laser feedback interferometry (PLFI).

3. Experimental results

To test the angle measurement accuracy, we compare our PLFI with the dual-frequency laser interferometer Agilent5529A, which has a claimed resolution of $0.05''$ and a displayed accuracy of $\pm 0.2\%$. The cube corner prism of the laser interferometer is fixed on an electrical rotation stage. The two beams of the PLFI directly impinge on the metal back of the angular retroreflector, which is a non-cooperative target with low reflectivity. The contrast results of the PLFI and the laser interferometer are determined by synchronously measuring the angle variation of the rotation stage. The proposed PLFI exhibits a good stability with the maximum nonlinear error $8''$ in a range of $1400''$, indicating that the accuracy of the PLFI is higher than $8''$. Figure 3 shows the contrast results and the nonlinear error. Another contrast experiment with autocollimator ELCOMAT3000 with a claimed accuracy of $0.25''$ shows a maximum nonlinear error of $4''$ within a range of $90''$, which verifies the precision of our PLFI.

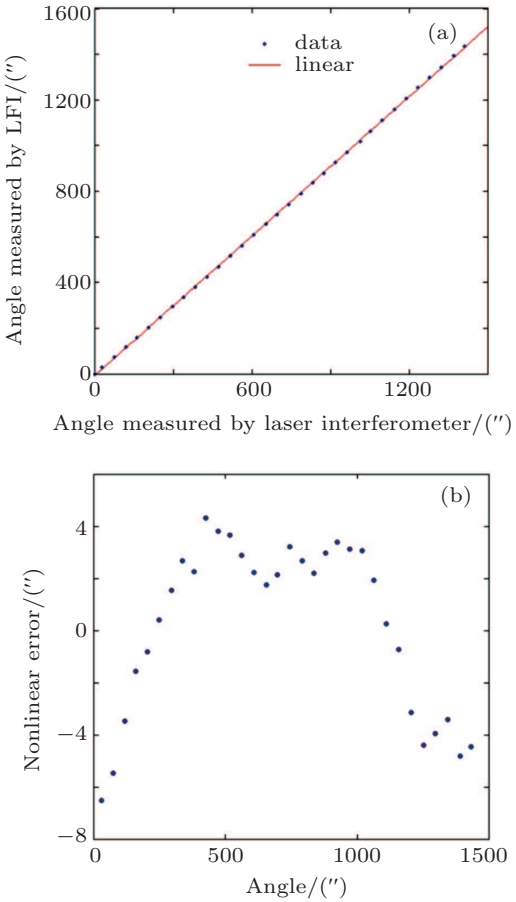


Fig. 3. (color online) (a) Contrast results and (b) nonlinear error.

Then we use the PLFI and dual-frequency laser interferometer Agilent 5529A to measure the yaw of a guide simultaneously. The angular retroreflector of the Agilent 5529A is fixed on the stage of the guide (Model GCMH-128). The two laser spots of the PLFI are directly irritated on the metal back of the angular retroreflector. The displacement difference of the two laser beams reflects the yaw of the guide. The measurement results of the PLFI and the Agilent 5529A are recorded simultaneously when the guide moves. The PLFI can also record the position since it measures the displacements of two positions of the target. The measurement results are shown in Fig. 4. The trends agree with each other but there are also some bad points which deserve further research. This experiment indicates the PLFI's ability of the non-contact yaw measurement of non-cooperative targets.

The angle measurement stability of the PLFI is tested by measuring a static target. The two laser beams impinge two

positions of the target. The target remains static. The measurement result is shown in Fig. 5. The final angle variation is limited within $\pm 1''$ for 5 min while both B1 and B2 have a drift about $6''$. This indicates that the PLFI eliminates the environmental disturbance to a large degree.

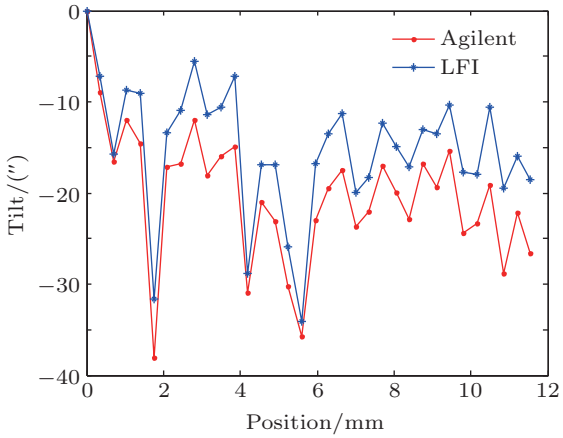


Fig. 4. (color online) Measurement results of the yaw of a guide.

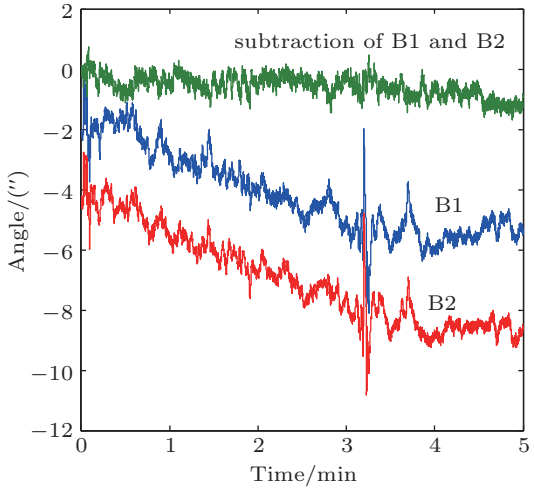


Fig. 5. (color online) Angle variations of B1, B2 and their subtraction.

Actually, the phase measurement result is the average phase of the small area irradiated by the laser. The diameter of the laser spots in our system is about 2 mm. When measuring the angle, the laser spots have transverse displacements on the target and the topography of the target may affect the measurement results. To estimate the error caused by the transverse displacements of the laser spots, we make the target move laterally and record the displacement variation. The target is a milled aluminum piece and mounted on the PI nanopositioning system (E753). The PI stage makes a triangle movement with an amplitude of 100 μm and a frequency of 0.4 Hz. Because the target is not absolutely perpendicular to the laser beam, there is an axial displacement too. The measurement results are shown in Fig. 6(a). The measurement displacement also has a triangle waveform with an amplitude of 1.4 μm. We extract the linear part and figure out the nonlinear error. The result is shown in Fig. 6(b). The nonlinear error reflects the measurement error caused by the transverse displacement. The result shows that the error is limited in ± 15 nm, corresponding to $\pm 1'$ angle error, which is acceptable in most measuring cases. Other targets like a mirror and other milled pieces (Ra 3. 2–0.8) are also measured and show similar results.

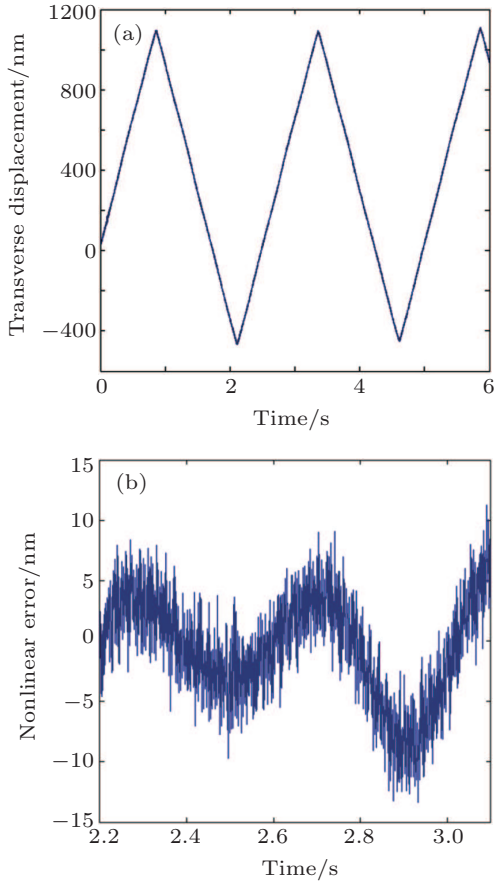


Fig. 6. (color online) Error caused by transverse displacement: (a) transverse displacement, (b) nonlinear error of the transverse displacement.

4. Discussion

In Ref. [9], the LFI still works even when the relative feedback power is as low as 10^{-13} (-130 dB).[9] Our experiment shows a higher result of 10^{-7} due to different experimental parameters and signal processing methods. We can also obtain a smaller value if we use a lock-in amplifier as the signal processing method, since the lock-in amplifier has a strong noise suppression ability but a low measurement speed.

5. Conclusion

In conclusion, a novel precise angle measurement scheme based on parallel multiplex laser feedback interferometry is presented and the direct non-contact angle measurement of the non-cooperative targets is realized. The experimental results indicate an accuracy of $8''$ with a range of $1400''$. Since the two

laser beams are close to each other, their subtraction can eliminate their common environment disturbance, thus the system has a good stability. The yaw of a guide can be easily measured using this scheme and the position can be recorded simultaneously since the two beams both measure the displacement. However, the laser interferometer needs a more complicated optical path to realize this function. This scheme can be expanded with more laser beams, and more dimensions and degrees of freedoms can be measured at the same time. For example, with three beams, the attitude of the target can be measured since three points determine a plane. Since the optical configuration is simple, the PLFI also has a small volume and is low cost.

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