Method for *in situ* calibration of multiple feedback interferometers

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A method is presented for *in situ* resolution calibration of multiple feedback interferometers (MFIs) using two lasers with different feedback levels simultaneously. The laser with weak optical feedback level generates half-wavelength optical fringes, whereas the laser with strong multiple feedback level generates optical nano-fringes. By using this method, the number of displaced optical nano-fringes can be easily counted, and the resolution of the MFIs can be accurately determined. The integrated MFIs can be used to measure displacements and calibrate other displacement sensors.

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Laser interferometry (LI) is a well-established method for measuring displacement, distance, and profile; it has the advantages of high accuracy, long-range capability, and multiaxis measurements[1,2]. However, in conventional LI, the optical resolution, which is no more than $\lambda/2$, is not suitable for precision measurements. To solve this problem, several methods, such as electric fringe subdivision, optical subdivision, and high-order feedback, have been proposed and utilized. The electric subdivision method can provide a subnanometer resolution by utilizing digital phase discrimination[3−5]. However, electric noises, polarization mixing, and ghost reflections can occur, resulting in nonlinearity errors[6−8]. The optical subdivision method, which can provide an optical scale factor of 1/16 via multiple-reflection principle[9,10], uses numerous optical elements in the optical system. The optical resolution is also difficult to improve. The laser feedback method has been widely studied because it has high resolution and compactness[11−14]. Tan *et al.*[11] obtained four optical fringes in half-wavelength displacement in Nd:YAG with an asymmetric external feedback cavity; the resolution of each fringe was $\lambda/8$. Mao *et al.*[12] observed seven optical fringes, with each fringe having a resolution of $\lambda/14$, in half-wavelength displacement in a He–Ne laser with strong multiple feedbacks. In the multiple feedback method, the fringe number in half-wavelength displacement can be more than 30, and the resolution can be higher than $\lambda/60$ without any electric subdivision. However, determining the exact number of fringes is difficult when the fringe density is very high because of the strong multiple feedback. Consequently, the exact resolutions of multiple feedback interferometers (MFIs) are unknown, which limits their applications in precision measurements.

In this letter, we propose a simple and effective method for *in situ* resolution calibration of MFIs using two lasers with different feedback levels to measure the displacement simultaneously. The laser with weak optical feedback level generates half-wavelength optical fringes, whereas the laser with strong multiple feedback generates high-density optical nano-fringes simultaneously. Thus, counting the number of optical nano-fringes that correspond to a half-wavelength displacement is easy, and the resolution of MFI is accurately obtained. The integrated MFI, which can measure the displacement and calibrate other displacement sensors, has been developed using *in situ* resolution calibration method.

The experimental setup for the *in situ* calibration of MFIs is shown in Fig. 1. Two He–Ne lasers were used. Laser A was composed of a plane mirror M_{A2} and a concave mirror M_{A1}, whereas laser B was composed of a plane mirror M_{B2} and a concave mirror M_{B1}. The radius of curvature of both M_{A1} and M_{B1} was 300 mm, and the reflection amplitude of the laser mirrors was $r_{A2} = r_{A1} = r_{B2} = r_{B1} = 0.996$. The laser capillary T was filled with 1:1 Ne^{20}–Ne^{22} gas mixture and 7:1 He–Ne gas mixture to suppress the Lamb dip in the output intensity curve. The inner diameter of the discharge tube was 0.9 mm. For lasers A and B, the length was 125 mm and the operating wavelength was 632.8 nm. M_{Af} and M_{Bf} were the feedback mirrors of lasers A and B, respectively. M_{Af} was a plane mirror with reflection amplitude of 0.04, whereas M_{Bf} was a concave mirror with reflection amplitude of 0.99. They were placed on the same stage (P) that can move sideways. Lasers A and B and M_{Af} and M_{Bf} were all placed in a single line to reduce the Abbe error as much as possible. D_A and D_B were photoelectric detectors.

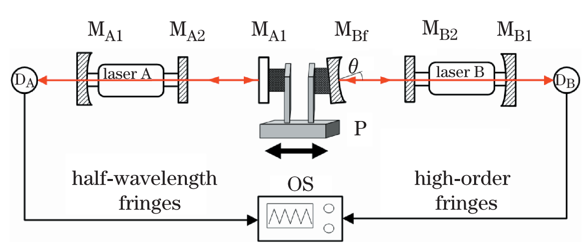

Fig. 1. *In situ* calibration setup. OS: oscilloscope.

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The first measurement demonstrated the relationship of the weak and strong multiple feedbacks in the *in situ* calibration system. The multiple feedback of laser A, which was subjected to M_{Af} with low amplitude reflectivity, was neglected. This phenomenon is the conventional weak feedback effect, in which one optical fringe corresponds to a half-wavelength displacement. Simultaneously, laser B was subjected to M_{Bf} with high amplitude reflectivity. The multiple feedbacks cannot be neglected because of the feedback beam reflection, which is also called high-order feedback beam, between M_{B2} and M_{Bf}. In particular, when the feedback mirror M_{Bf} is tilted at angle θ, many high-order feedback beams can re-enter the laser resonance cavity. High-density optical nano-fringes can then be obtained. The fringe density of a high-order feedback changes with the variation of the tilt angle.

Figure. 2 shows the intensity curves of the two lasers when the lengths of their feedback cavities are modulated simultaneously by stage P. The I_c curve was the conventional feedback curve of laser A, whereas the I_h curve was the multiple high-order feedback curve of laser B. The bottom curve was the driving voltage of stage P. The voltage range was from 0 to 200 V, corresponding to the extension displacement from about 0 to 0.9 μm.

Figure 2(a) presents the *in situ* resolution calibration results when the tilt angle of M_{Bf} is 0.5°. About three fringes were in the conventional weak feedback on the down-cycle of the driving voltage and about nine fringes were in the strong high-order feedback on the same driving cycle. In the half-wavelength fringe of the weak feedback, three fringes were in the strong high-order feedback. Thus, the resolution of the high-order feedback system was $\lambda/6$.

When $\theta = 1.2°$, the fringe density of strong high-order feedback improved remarkably, as shown in Figs. 2(b) and (c). The total number of high-order fringes on the down cycle of the driving voltage was now difficult to determine, but the number of fringes that corresponds to the half-wavelength fringe can be obtained. Thus, the resolution of $\lambda/36$ was obtained.

When the tilt angle θ was increased to 1.8°, a higher fringe density was obtained, as shown in Figs. 2(d) and (e). In Fig. 2(d), the modulation depth of each fringe was non-uniform and more fringes were generated within the same driving cycle. The non-uniformity of the fringes may have resulted from the superimposition of multiple high-order feedback and the differences in the intensity of each high-order feedback beam. Figure 2(e) shows that in each half-wavelength fringe in the weak feedback, 33 fringes were in the high-order feedback, indicating that the feedback mirror had a resolution of $\lambda/66$ and that the system generated one optical fringe. For a 632.8-nm He–Ne laser, the resolution can reach 9.6 nm, which is satisfactory in most application fields. In addition, the feedback system can be directly traced to the wavelength of light, so it has a great potential in calibrating other displacement sensors.

The second measurement was used to estimate the feasibility of the *in situ* calibration of MFIs. In Fig. 3, the MFI was compared with the HP (5517D) interferometer in measuring displacements. The tilt angle of MFI was 1.8° and the resolution was 9.6 nm. The feedback mirror (M_{Bf}) of MFI and the target mirror of HP interferometer were both set on the Physik Instrumente (PI) nanopositioning stage, which has 0.4-nm resolution and 2-nm repeatability. The PI stage was controlled by the closed-loop controller E-753.1CD that can move from 0 to 100 μm. The displacement measurement of MFI can be expressed as $N\delta$, where N is the number of optical fringes and δ is the pulse equivalent (resolution) obtained using the *in situ* calibration method.

When the PI stage was moved by 10 μm, the displacement was measured using the MFI and the HP interferometer simultaneously. In Fig. 4, the measured results of MFI coincide with that of the HP interferometer. The linearity of MFI measurements was about 4.5 $\times 10^{-5}$ in a 100-μm range. The experimental results proved the feasibility of the *in situ* calibration method for MFI to calibrate other displacement sensors.

In conclusion, a simple and effective *in situ* calibration method for MFIs using feedback from two lasers is proposed. Conventional half-wavelength optical fringes and high-order optical fringes are obtained simultaneously. The number of high-order fringes that correspond to a half-wavelength fringe is easily identified, and the MFI

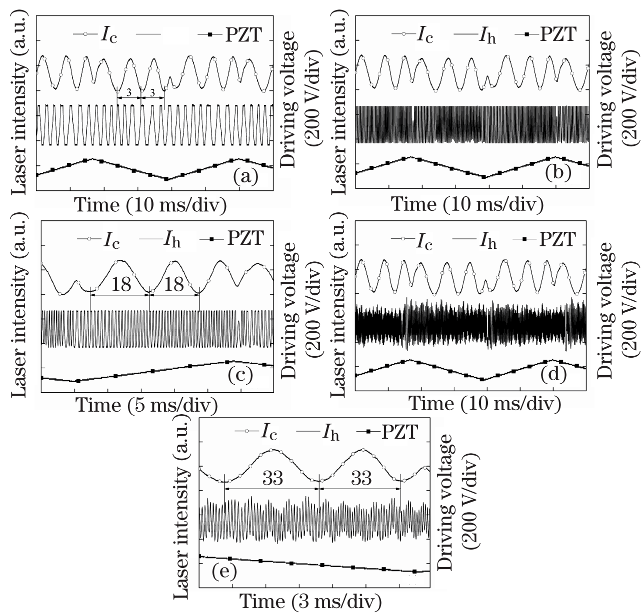

Fig. 2. Intensity curves of two lasers with different tilt angles: (a) $\theta = 0.5°$ and (b) $\theta = 1.2°$; (c) on an enlarged time scale of (b); (d) $\theta = 1.8°$; (e) on an enlarged time scale of (d).

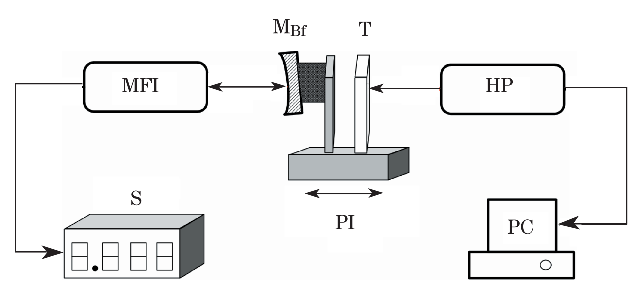

Fig. 3. Experimental setup of MFI and HP interferometer. T: target mirror of HP interferometer; S: electric cabinet of MFI; PC: computer.

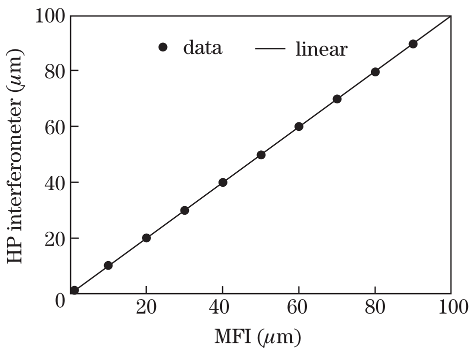

Fig. 4. Results obtained using MFI and HP interferometer.

resolution is accurately determined. The experimental results prove the feasibility of *in situ* calibration method for MFI using feedback from two lasers. The method is intuitive, simple, accurate, and traceable. The *in situ* calibration method is used to develop integrated MFIs with high optical resolution of $\lambda/66$, which can be used to measure displacements and calibrate other displacement sensors.

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