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Collimation testing and calibration using a heterodyne Moiré method

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ABSTRACT

This study proposes a simple, rapid, and highly accurate method to achieve the collimation testing and calibration of laser light beams. By applying a relative constant velocity to two gratings, every pixel of a CMOS camera can receive a series of heterodyne moiré signals. Based on the least squares sine fitting algorithm, the phase of the optimized sinusoidal wave can be obtained. Consequently, the phase slope along the direction perpendicular to the grating lines can be estimated and then used to judge the degree of collimation. Furthermore, by measuring only two phase slopes at two positions of the collimating lens, the calibration of the light beam collimation can also be achieved. The experiment validated the proposed method, and the positioning error of the light beam collimation was approximately 7 μm.

1. Introduction

In the procedures for assembling numerous types of optical systems, the collimation degree of an expanded laser light beam can strongly affect the performance of the entire system. Evidently, the collimation testing and calibration of a laser light beam play crucial roles in installing an optical system. Moiré interferometry is widely studied and applied in collimation testing because it features a simple and economic optical configuration, high accuracy, and high resolution. The accuracy of collimation testing is defined as the smallest detectable deviation of the collimating lens in the collimation position [1,2], and several research groups are devoted to improving the testing accuracy by developing novel optical configurations or new signal analysis methods for the collimation testing system. Shakher used the self-image effect of circular grating [3] and Mehta used the self-image effect of specially designed grating [4] to observe the Moiré images for determining the collimation position. Because both methods cannot quantitatively determine the variation of the Moiré patterns, the measurement errors are larger than those of the quantitative methods. The collimation testing techniques involving the use of the self-image effect of Ronchi gratings are often applied to quantitative collimation testing because the Moiré pattern of the Ronchi gratings can be regarded as a sinusoidal variation and is simple to analyze. Torroba and Mudassar measured the spatial frequencies of the Moiré fringes to determine the collimation position [5–7], but large errors can be introduced near the collimation position. When Moiré fringes are lower than one period, the harmonic noise of Moiré dramatically affects the low-frequency Moiré fringes. Prakash determined the collimation position more accurately by using the phase-shifting technique [8] and the Fourier transform method [2] to analyze the phase distribution of the Moiré fringes. All of the aforementioned methods are used for determining the collimation position by using the criteria obtained from the principle of the proposed testing system. However, when the light beam is used to calibrate the collimation, the procedures are trivial and time-consuming because the collimating lens must scan and test along the optical axis until the test result matches the criteria. Therefore, this study proposes a simple, rapid, and highly accurate method to achieve the collimation testing and calibration of laser light beams. The collimation position of the collimating lens can be determined by measuring the phase slopes of the Moiré fringes at two positions of the collimating lens. In addition, by using the concept of heterodyne interferometry to analyze the phase distribution of the Moiré fringes, the measured phases and phase slopes are less influenced by the instability of the light source and the disturbance of the environment. The positioning error of the collimating lens in the collimation position can achieve approximately 7 μm under experimental conditions.

2. Principle

Fig. 1 shows the optical configuration of the proposed collimation testing system. When a laser light beam at a wavelength of λ

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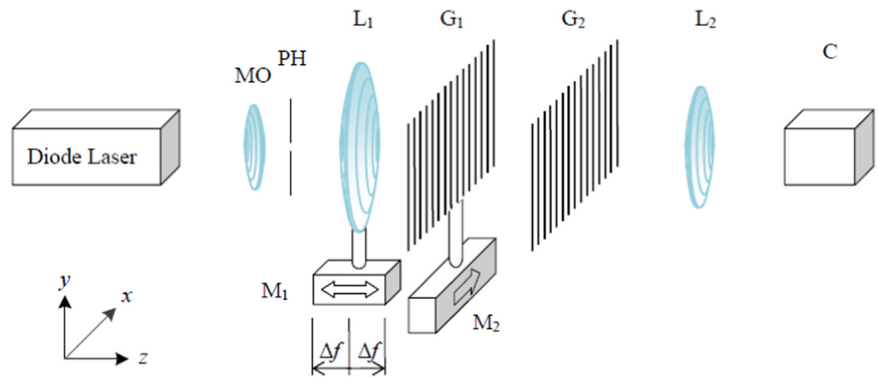

Fig. 1. Optical configuration. MO: objective; PH: pinhole; L_1: collimating lens; L_2: camera lens; G_1 and G_2: gratings; M_1 and M_2: motorized translation stages; C: CMOS camera; and Δf: displacement from collimation position.

passes through an objective, a pinhole, and a collimating lens mounted on the motorized translation stage M_1 to form an expanded and collimated light beam, it then impinges on the grating G_1 mounted on the motorized translation stage M_2 to generate the self-images. The first self-image of G_1 is projected on the grating G_2 to form the Moiré fringes, and the first self-image distance Z_1 can be expressed as

$$Z_1 = \frac{p^2}{\lambda}, \tag{1}$$

where p is the grating pitch of the gratings G_1 and G_2. The grating G_1 is moved by the motorized translation stage M_2 at a constant velocity v along the x-axis, and the collimating lens deviates from the collimation position with a distance of Δf to cause the light beam to exhibit convergence or divergence and thus the light beam generate a deflection angle. Assuming the deflection angle is small, and according to the Fresnel diffraction formula, every pixel of a CMOS camera can receive a series of time-varying heterodyne Moiré signals [8,9]:

$$I(x,y,\Delta f,t) = \frac{1}{4} - \frac{2}{\pi^2}\cos\left[2\pi f_h t + \varphi(x,y,\Delta f)\right], \tag{2}$$

where $f_h = v/p$ is the heterodyne frequency that results from the time-varying phase difference. $\varphi(x, y, \Delta f)$ is the phase distribution of the Moiré fringes and can be expressed as

$$\varphi(x,y,\Delta f) = \frac{2\pi}{p} u(x,y,\Delta f) Z_1 + \phi, \tag{3}$$

where ϕ is the addition phase that results from the initial displacement between the gratings G_1 and G_2, and $u(x, y, \Delta f)$ is the deflection angle of the light beam. Because only the x-component of the deflection angle can affect the phase distribution of the Moiré fringes, $u(x, y, \Delta f)$ can be expressed as

$$u(x,y,\Delta f) = \frac{x}{R + Z_1}, \tag{4}$$

where R is the curvature radius of the wavefront of the discollimation light beam. When the light beam approaches collimation, R is substantially greater than Z_1. By differentiating Eq. (4) with respect to x, the phase slope of the Moiré fringes along the x-axis can be obtained:

$$\theta(\Delta f) = \frac{d\varphi}{dx} \cong \frac{2\pi Z_1}{pR}, \tag{5}$$

According to Eq. (5), the criteria of the collimation degree can be determined: (1) when the light beam is collimated, namely $\Delta f = 0$ and R approaches infinity, the phase slope of the Moiré fringes $\theta = 0$; (2) when the light beam is divergent, namely $\Delta f < 0$ and $R > 0$, $\theta > 0$; and (3) when the light beam is convergent, namely $\Delta f > 0$ and $R < 0$, $\theta < 0$. Therefore, the phase slope θ of the Moiré fringes along the x-axis can be estimated by measuring the phase distribution $\varphi(x, y)$ of the Moiré fringes, and can be used to judge the degree of collimation and calibrate the collimation of the light beam simultaneously. To extract the phase distribution of the Moiré fringes, Eq. (2) can be rewritten as

$$I(x,y,\Delta f,t) = A\cos(2\pi f_h t) + B\sin(2\pi f_h t) + C, \tag{6}$$

where A, B, and C are real numbers, and

$$\varphi(x,y,\Delta f) = \tan^{-1}\left(\frac{-B}{A}\right), \tag{7}$$

where A and B can be obtained by using the least squares sine fitting algorithm [10]. The phase slope θ can also be estimated by differentiating the phase distribution φ with respect to x, and then the degree of collimation can be determined. Additionally, the curvature radii R of the light beam near the front and back collimation positions are approximately equal and have opposite signs. According to Eq. (5), the phase slopes near the collimation position exhibit a linear variation. When the optical system is initially assembled using the naked eye, the phase distribution of the Moiré fringes can be measured to obtain the phase slope θ_1. By subsequently moving the collimating lens with a value of z_d along the z-direction ($z_d > 0$) or along the $-z$-direction ($z_d < 0$), the phase slope can be measured as θ_2. Considering the linear variation of the phase slope near the collimation position, the calibration distance z_c can be calculated:

$$z_c = -\frac{z_d \theta_2}{|\theta_2 - \theta_1|}. \tag{8}$$

Therefore, the collimation position $\Delta f = 0$ can be determined by moving the collimating lens with z_c. Because the collimating lens is not required to scan and test along the optical axis in the proposed method, this system can rapidly and accurately perform light beam collimation testing and calibration.

3. Experiments and results

The collimation testing and calibration system was implemented to validate the proposed method. The optical configuration included a diode laser at a wavelength of 473 nm, a 40× objective, a pinhole of 5 μm, an achromatic lens featuring a focal length of 100 mm as a collimating lens, two linear gratings exhibiting a pitch of 0.2822 mm, and two motorized translation stages (Sigma Koki/SGSP(MS)26-100), M_1 and M_2, with a resolution of 0.05 μm. M_1 was used to control the position of the collimating lens and M_2 was used to generate a heterodyne frequency $f_h = 10$ Hz ($v = 2.822$ mm/s). A CMOS camera (Basler/A504k) featuring an 8-bit gray level and an image resolution of 1280 × 1024 was used to record the heterodyne Moiré signals at various times at a frame rate $f_s = 150$ fp s, exposure time $a = 1$ m s,

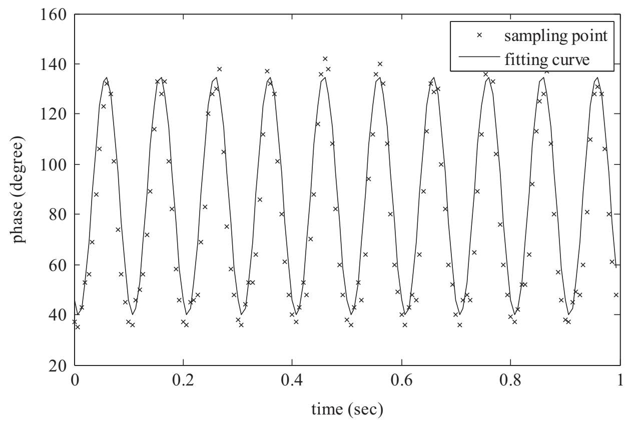

Fig. 2. Heterodyne Moiré signal of one representative pixel recorded by CMOS camera.

and total recording time $T=1$ s. Two-dimensional median filtering was applied to every recorded Moiré image by using a 3×1 window to filter the grating noise of the Moiré fringes [11]. Then, applying the least squares sine fitting algorithm to every pixel, the phase of the heterodyne Moiré signal of every pixel can be calculated. Figs. 2–5 show the experimental results of the collimation testing. The heterodyne Moiré signal of one pixel can be seen in Fig. 2. Fig. 3 (a), (b), and (c) shows the measured phase distribution in the positions of $\Delta f=0$ and $\Delta f=\pm300$ μm. Fig. 4(a), (b), and (c) shows the phase curves captured along the x-axis and through the center of the image (namely, the optical axis) in Fig. 3(a), (b), and (c). The linear line segments $F(\theta,\ \delta)=\theta x+\delta$ were simultaneously plotted using the least squares method of polynomial fit to obtain the phase slope θ. Figs. 3(a) and 4(a) can obviously be judged as $\theta>0$ when $\Delta f<0$, and the light beam is divergent. As shown in Figs. 3(b) and 4 (b), the phase distribution suffered from the large harmonic noise of the moiré fringes when the light beam was collimated, $\Delta f=0$. However, the phase slope $\theta\simeq0$ could also be estimated using the polynomial fit. Figs. 3(c) and 4(c) show $\theta<0$ when $\Delta f>0$, and indicate that the light beam is convergent. To inspect the smallest detectable deviation of the collimating testing system, the system implemented 10 measurements in the positions of $\Delta f=0$ and $\Delta f=\pm8$ μm, as shown in Fig. 5. The phase slopes measured in the position of $\Delta f=0$ lie from 0.8314 rad/m to -0.9118 rad/m, and do not overlap the phase slopes measured in the positions of $\Delta f=\pm8$ μm. Therefore, the smallest detectable deviation of the proposed system can be below 16 μm, and the repeatability of the phase slope can be estimated as 1.7432 rad/m by observing the phase fluctuation in Fig. 5(a), (b), and (c). To validate the property of the linear variation of the phase slope near the collimation position, the phase slopes were measured by considering the interval of 50 μm between $\Delta f=\pm1000$ μm. The experimental results are shown in Fig. 6 and indicate the same property of the linear variation of the phase slope in Eq. (5). By using this linear property, the rapid calibration of the light beam collimation can be achieved. Fig. 7 shows the experimental results of the calibration. Fig. 7(a) shows the measured phase curve, fitted line segment, and estimated phase slope θ_1. Fig. 7(b) shows the measured phase curve, fitted line segment, and estimated phase slope θ_2 after the collimating lens was moved by $z_d=300$ μm. By substituting θ_1 and θ_2 into Eq. (8), $z_c=-260.5$ μm can be obtained. Consequently, the collimation position of the light beam can be calibrated by moving the collimating lens along the $-z$-axis by 260.5 μm. Fig. 7(c) shows the measured phase curve, fitted line segment, and estimated phase slope in this collimation position. The estimated phase slope lies within the repeatability of the phase slope 1.7432 rad/m and can therefore prove the feasibility of the proposed method.

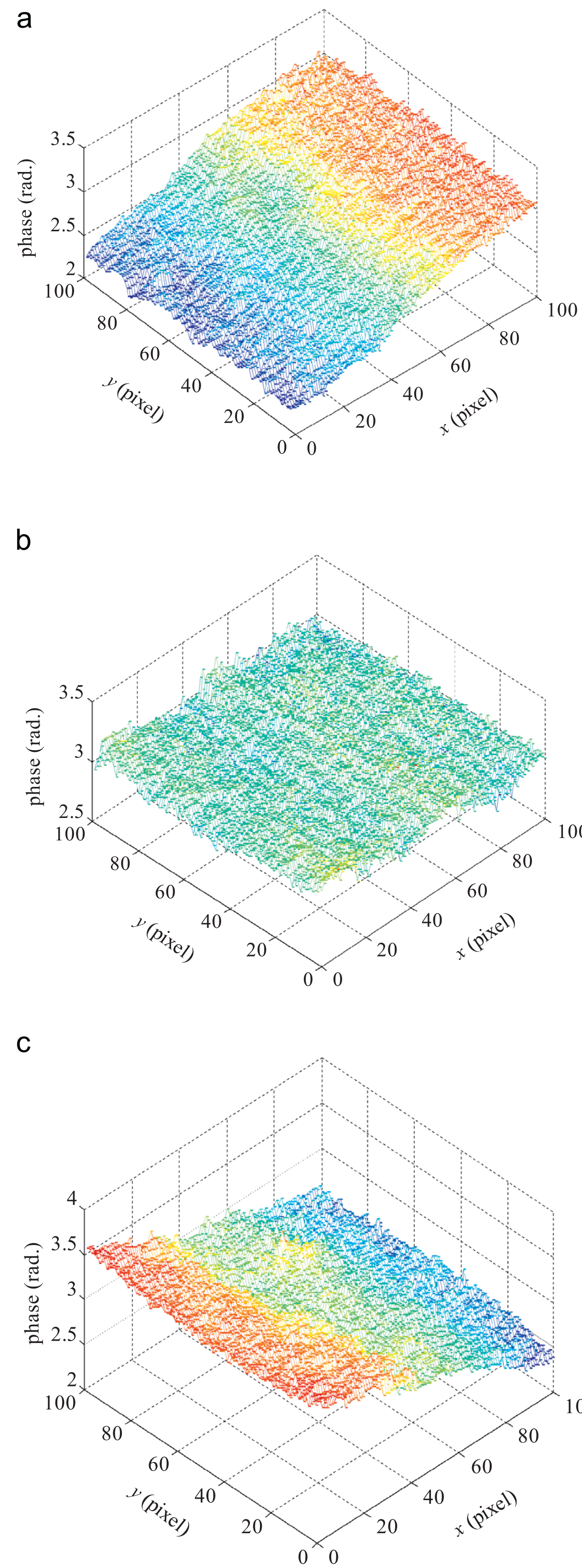

Fig. 3. Phase distribution maps. (a) $\Delta f=-300$ μm; (b) $\Delta f=0$ μm; and (c) $\Delta f=300$ μm.

4. Discussions

The sensitivity of the proposed method can be deduced by incorporating the concept of the geometric optics. When the light

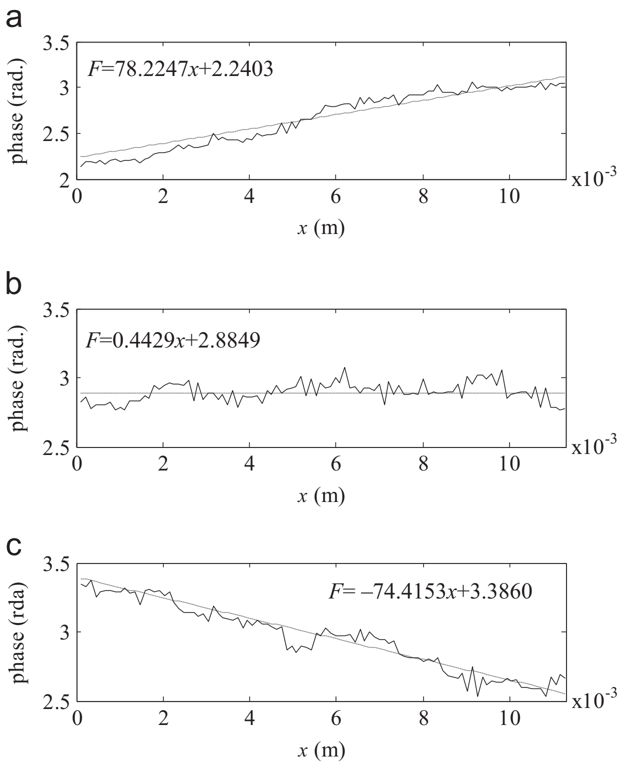

Fig. 4. Phase curves plotted along the *x*-axis and through the center of the image (namely, the optical axis) in Fig. 2(a), (b), and (c). Solid lines denote the measured phase curves and dashed lines denote fitted data. (a) $\Delta f = -300\ \mu m$; (b) $\Delta f = 0\ \mu m$; and (c) $\Delta f = 300\ \mu m$.

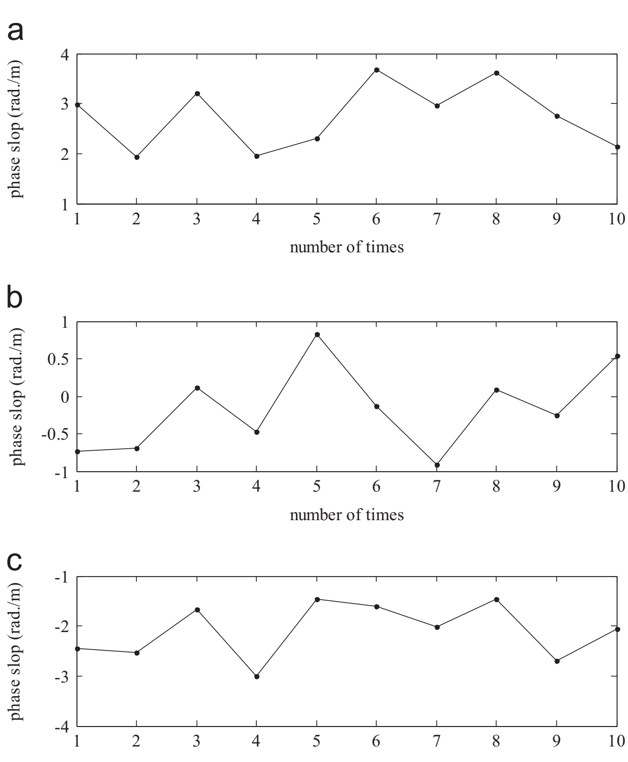

Fig. 5. Phase slop curves by repeating testing. (a) $\Delta f = -8\ \mu m$; (b) $\Delta f = 0\ \mu m$; and (c) $\Delta f = 8\ \mu m$.

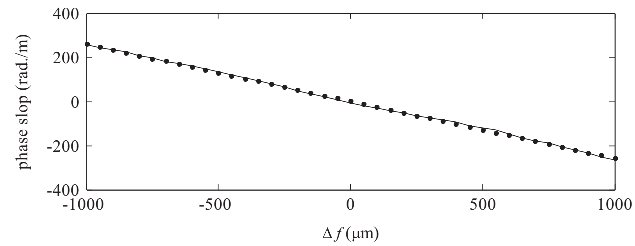

Fig. 6. Phase slop curves by testing along the optical axis. Black dots denote the measured data and solid line denote fitted data.

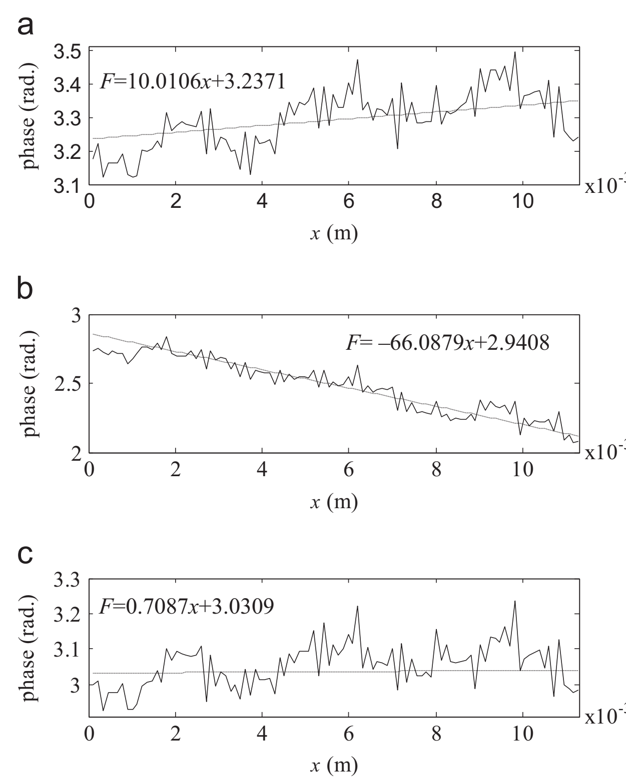

Fig. 7. Experimental results of light beam calibration. Solid lines denote the measured phase curves and dashed lines denote fitted data. (a) $z_d = 0\ \mu m$; (b) $z_d = 300\ \mu m$; and (c) $z_c = -260.5\ \mu m$.

beam is close to collimation, the ray tracing of a thin lens can be assumed to describe that the small deflection angle is altered by the refractive power of the collimating lens and can be derived by the following formula

$$\frac{du(x,y,\Delta f)}{dx} = -\frac{\Delta f}{f^2}. \tag{9}$$

where f is the focal length of the collimating lens. According to Eqs. (3) and (9), the phase slope can be expressed in the following form:

$$\theta(\Delta f) = -\frac{2\pi Z_1}{pf^2}\Delta f. \tag{10}$$

Therefore, the sensitivity S of the collimation testing method can be derived as

$$S = \left|\frac{d\theta}{d(\Delta f)}\right|_{\Delta f} = \left.\frac{2\pi Z_1}{pf^2}\right|_{\Delta f} = \left.\frac{2\pi p}{\lambda f^2}\right|_{\Delta f}, \tag{11}$$

which indicates the ability of phase slope change when moving the collimating lens per unit length, and simultaneously indicates the constant change of the phase slope within the close collimation position. Fig. 8(a) and (b) shows the sensitivity plots of the proposed method. For ease to understanding, the unit of sensitivity has been set as the phase slope per micrometer, namely rad/(m · μm). Fig. 8(a) displays the plot of sensitivity versus the grating pitch while the focal length of the collimating lens is 100 mm. In closely collimation region, namely the deflection angle is very small, the sensitivity is proportional to the grating pitch as shown in Eq. (11), and the distance Z_1 between two gratings obviously dominates the sensitivity of the proposed method. However, although the smaller grating pitch has the ability to increase the phase slope, itbut can also sharply shortens the self-image distance Z_1 and consequently reduces the sensitivity. Fig. 8(b) displays the plot of sensitivity versus focal length of the collimating lens and shows the normality that a smaller focal length has a larger refractive power and leads to a larger sensitivity of phase slope. Therefore, increasing the grating pitch can improve the measurement sensitivity. But the large optical setup is not expected for designers. So the grating pitch should be chosen by determining the sensitivity that the users would like to achieve when using different collimating lens.

The phase slope of the proposed method is acquired by the optimized line segment $F(\theta, \delta)=\theta x+\delta$ using the least squares method of polynomial fit and can be expressed as

$$residue=\frac{1}{N}\sum_{i=0}^{N-1}(F_i-\phi_i)^2, \tag{12}$$

where N denotes the sampling points in x-axis, F_i denotes the ith fitting data of phase, and φ_i denotes the ith sampling data of phase. The coefficients θ and δ can be obtained by minimizing the residue of Eq. (12). The standard error $\Delta\theta_s$ of the resultant phase slop θ can be expressed as [12]

$$\Delta\theta_s=\frac{s}{\sqrt{ss_{xx}}}, \tag{13}$$

and

$$s=\sqrt{\frac{ss_{\varphi\varphi}-(ss_{x\varphi}^2/ss_{xx})}{N-2}}, \tag{14a}$$

$$ss_{xx}=\sum_{i=1}^{N}(x_i-\overline{x})^2, \tag{14b}$$

$$ss_{\varphi\varphi}=\sum_{i=1}^{N}(\varphi_i-\overline{\varphi})^2, \tag{14c}$$

$$ss_{x\varphi}=\sum_{i=1}^{N}(x_i-\overline{x})(\varphi_i-\overline{\varphi}), \tag{14d}$$

where $\overline{x}$ and $\overline{\varphi}$ denote the arithmetic means of x and y, respectively. Substituting the experimental conditions and the random error with the amplitude, which is set to be the phase error of the heterodyne Moiré signal as 0.9° [10], the standard error $\Delta\theta_s$ can be estimated as 0.1343 rad/m. But the harmonic noise strongly affects the phase distribution of moiré when the collimating lens is close to the collimation position, as shown in Fig. 4. Hence, the amplitude of random error can accordingly be set to be 0.2 rad and the standard error $\Delta\theta_s$ can subsequently be estimated as 1.7859 rad/m. The resultant standard error $\Delta\theta_s$ is larger than and close to the repeatability of the phase slope in the experiment, and can therefore prove the validity of the error analysis of the proposed method.

Furthermore, According to Eq. (8), the positioning error Δz_c of the proposed calibration method can be expressed as

$$\Delta z_c=\left|\frac{\theta_2}{\theta_2-\theta_1}\right||\Delta z_d|+\left|\frac{z_d\theta_2}{(\theta_2-\theta_1)^2}\right||\Delta\theta_1|+\left|\frac{z_d\theta_1}{(\theta_2-\theta_1)^2}\right||\Delta\theta_2|, \tag{15}$$

where Δz_d is the displacement error of the collimating lens, and $\Delta\theta_1$ and $\Delta\theta_2$ are the phase slope errors. The displacement error of the collimating lens is introduced by the resolution of the motorized translation stage, and can be estimated as approximately 0.05 μm. The phase slope error is introduced by the error of phase slope measurement. The phase slope errors $\Delta\theta_1$ and $\Delta\theta_2$ can be set as the standard error $\Delta\theta_s$=1.7859 rad/m. By substituting Δz_d, $\Delta\theta_1$, $\Delta\theta_2$, and the experimental conditions into Eq. (15), the positioning error Δz_c of the proposed calibration method was approximately 7 μm.

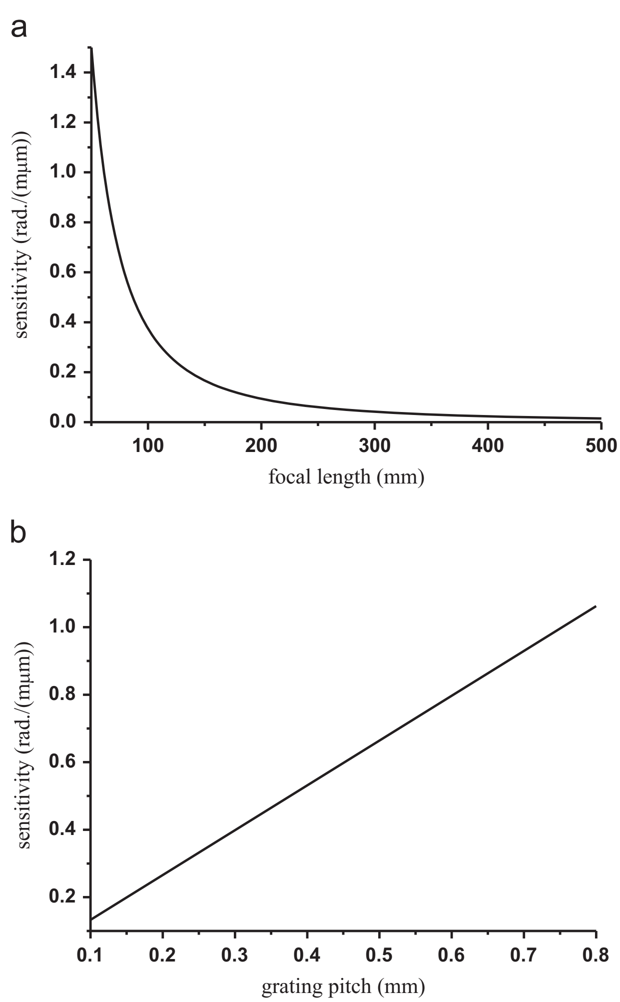

Fig. 8. Sensitivity plots. (a) Sensitivity versus grating pitch in experimental condition and (b) sensitivity versus focal length of collimating lens in experimental condition.

5. Conclusions

This paper proposed a simple, rapid, and highly accurate method to achieve the collimation testing and calibration of laser light beams. By applying a relative constant velocity to two gratings, every pixel of a CMOS camera can receive a series of heterodyne Moiré signals. Based on the least squares sine fitting algorithm, the phase of the optimized sinusoidal wave can be obtained. Subsequently, the phase slope along the direction perpendicular to the grating lines can also be estimated and be used to quantitatively determine the degree of light beam collimation. In addition, only two phase slopes in two positions of the collimating lens must be measured to acquire the collimation position because the calibration of the light beam collimation is performed rapidly and accurately using the proposed method. Because the phase distribution of the Moiré fringes is analyzed using the concept of heterodyne interferometry, the measured phases and phase slopes are less influenced by the instability of the light source and the disturbance of the environment. The experiment validated the proposed method, and the positioning error of the proposed calibration method was approximately 7 μm. This method exhibits the merits of simplicity, rapidity, and high accuracy because of the introduction of Moiré interferometry, the Talbot effect, and heterodyne interferometry.

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