A multi-wavelength heterodyne optical zooming method based on double grating interferometer

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Abstract. A multi-wavelength heterodyne optical zooming method based on double grating interferometer was proposed for nanometer measurement. The zooming factor $K$ can be adjusted easily by changing the wavelength striking on a sensing mirror and two compensating mirrors, allowing us to measure the displacement with different accuracy by using the same laser sources. Moreover, the heterodyne signal generated by vibrating a grating ensures the measurement of displacement with high signal to noise ratio.

1. Introduction
Optical interferometric method is widely used to measure the displacement with a subnanometer resolution. Many types of high precision sensor have been developed in various research fields. Optical zooming technique is one of the nano-metrology methods with high resolution. Matsumoto and Minoshima reported a self-zooming optical scale based two-color interferometer. Zhao proposed a dual wavelength parallel interferometer; the displacement in the sensing mirror in nanometer order can be compensated by moving a reference mirror to several micrometers. The key technique in these zooming methods is compensating a nanometer displacement by $K$-times as large displacement. If the uncertainty in phase measurement of interference fringe is the same, the accuracy increases $K$-times by using zooming method. In conventional zooming method, the factor $K$ is unchangeable for the given laser source.

Here we propose a multi-wavelength heterodyne optical zooming method for nanometer measurement. The zooming factor $K$ can be adjusted easily according to different measurement accuracy by using the same laser sources. Moreover, the heterodyne technique ensures to measure the displacement with high signal to noise ratio.

2. Optical system
Figure 1 shows the principle of the zooming method. Three coaxially mixed laser beams, denoted by $I_0$, strike on a grating $G_1$ at normal incidence. The $\pm 1^\text{st}$ order diffraction beams of three wavelengths then are incident on a grating $G_2$ that is with the same period of $G_1$ and placed parallel with $G_1$. Laser beams diffracted by $G_2$ are parallel with $I_0$. $+1^\text{st}$ (or $-1^\text{st}$) order diffracted beams $I_1$, $I_2$ and $I_3$ (or $I_{-1}$, $I_{-2}$ and $I_{-3}$) are with respect to the wavelengths $\lambda_1$, $\lambda_2$ and $\lambda_3$. Beams $I_1$ reflects on mirror $M_1$, $I_1$ and $I_2$ on $M_2$, $I_2$ and $I_3$ on $M_3$, and $I_{-3}$ on $M_4$. The interference signals with respect to three wavelengths are detected by detectors $D_1$, $D_2$ and $D_3$. 

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A small displacement $\Delta$ in sensing mirror $M_1$ results in variation in phase difference between $\lambda_1$ and $\lambda_2$, which then is compensated by moving the compensating mirror $M_2$ a large distance $\Delta'$.

$$\Delta' = \frac{n_1 \lambda_{s12}}{n_{s12} \lambda_n} \Delta,$$

where $n_1$ and $n_2$ are refractive indices of air, $n_{s12}$ is group refractive index, $\lambda_{s12}$ are synthetic wavelength of $\lambda_1$ and $\lambda_2$. Similarly, the displacement $\Delta'$ results in variation in phase difference between $\lambda_2$ and $\lambda_3$, which then is compensated by moving $M_3$ a much larger distance $\Delta''$. Therefore, a small displacement $\Delta$ results in a $K$-times large displacement $\Delta''$, and is expressed by

$$\Delta'' = \frac{n_2 \lambda_{s23}}{n_{s23} \lambda_n} \frac{n_1 \lambda_{s12}}{n_{s12} \lambda_n} \Delta = K \Delta,$$

If we use three He-Ne lasers with wavelengths of $\lambda_1=0.594 \, \mu m$, $\lambda_2=0.612 \, \mu m$ and $\lambda_3=0.633 \, \mu m$, the zooming factor $K=1025$.

We can adjust the zooming factor $K$ by changing the positions of $M_1$-$M_4$. Consider beams $I_1$ reflect on $M_1$, $I_2$ and $I_3$ on $M_2$, $I_1$ and $I_2$ on $M_3$, and $I_1$ on $M_4$. Similarly, a small displacement $\Delta$ in $M_1$ can be compensated by moving $M_2$ and then $M_3$ in order, in the case, $K=962$. Table 1 shows $K$ caused by different sensing mirror and compensative mirrors. $K$ varies when different wavelength strikes on different mirror. The displacement in sensing mirror is denoted by $\Delta$, and that in compensating mirrors by $\Delta'$ and $\Delta''$. The zooming factor $K$ can be adjusted easily using the same laser sources.

Table 1 Different factor $K$ caused by different sensing mirror and compensative mirror

| $K$  | $\Delta$       | $\Delta'$       | $\Delta''$       |
|------|----------------|-----------------|------------------|
| 1025 | $\lambda_1=0.594 \mu m$ | $\lambda_1=0.594 \mu m, \lambda_2=0.612 \mu m, \lambda_3=0.633 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_3=0.633 \mu m$ |
| 473  | $\lambda_1=0.594 \mu m$ | $\lambda_1=0.594 \mu m, \lambda_2=0.612 \mu m, \lambda_3=0.633 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_3=0.633 \mu m$ |
| 536  | $\lambda_2=0.612 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_1=0.594 \mu m, \lambda_3=0.633 \mu m$ | $\lambda_1=0.594 \mu m, \lambda_3=0.633 \mu m$ |
| 619  | $\lambda_2=0.612 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_3=0.633 \mu m$ | $\lambda_3=0.633 \mu m, \lambda_1=0.594 \mu m, \lambda_2=0.612 \mu m$ |
| 518  | $\lambda_3=0.633 \mu m$ | $\lambda_3=0.633 \mu m, \lambda_2=0.612 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_1=0.594 \mu m, \lambda_3=0.633 \mu m$ |
| 962  | $\lambda_3=0.633 \mu m$ | $\lambda_3=0.633 \mu m, \lambda_2=0.612 \mu m$ | $\lambda_2=0.612 \mu m, \lambda_1=0.594 \mu m, \lambda_3=0.633 \mu m$ |
The vibration of G₁ generates heterodyne signal, allowing us to measure the displacement with high signal to noise ratio. When G₁ moves perpendicular to both its normal and the grooves, the frequency shift $\Delta f$ of the $m$th diffraction order is expressed as

$$\Delta f = \frac{mv}{d},$$

where $v$ is the moving velocity, and $d$ is the period of the grating. The total frequency shift between the two interference beams is $4\Delta f$. In the experiment, grating G₁ is glued on a PZT, which is driven by a sine voltage. The heterodyne signal $I_s(t)$ detected by the detector can be written as

$$I_s(t) = a_s + b_s \cos[\phi_s \cos(\omega t) + \Delta \phi],$$

where $a_s$ and $b_s$ are constants, $\phi_s$ is the depth of modulation that can be changed by varying the amplitude of the modulation signal, $\omega_s$ is the angular frequency of modulation signal, and $\Delta \phi$ is the phase difference to be measured. A signal processing circuit is implemented to transfer $I_s(t)$ to a cosine signal.

$$I = C_0 \cos(\omega t - \Delta \phi),$$

where $C_0$ is the amplitude of the interference signal. $I$ is a standard cosine signal; the phase included can be obtained by using a phase meter or a lock-in amplifier.

3. Experimental results

The grating G₁ used in the experiment has a groove density of 850 mm⁻¹. The vibration frequency of G₁ is 1 kHz. Optical setup is shown in Fig.1. The factor $K=1025$.

Moving the sensing mirror M₁ with a step of 8 nm up to 56 nm by a PZT stage, and measuring the displacement by a grating scale fixed on PZT stage, the displacement $\Delta$ results a variation in phase difference between $\phi_1$ and $\phi_2$ (with respect to $\lambda_1$ and $\lambda_2$). The phase difference was then compensated by moving the compensating mirror M₂ a displacement $\Delta'$. Similarly, the movement of M₂ results in a variation in phase difference between $\phi_2$ and $\phi_3$ (with respect to $\lambda_2$ and $\lambda_3$), which was compensated by moving M₃ a displacement $\Delta''$. $\Delta'$ and $\Delta''$ are measured by using a linear gauge with a resolution of 20 nm. Figures 2a and 2b show the $\Delta$ obtained from $\Delta'$ and $\Delta''$. Using the displacement measured by a grating scale as a reference, the standard deviations are 3.8 nm and 3.9 nm, and the slopes of fitting line are 1.12 and 1.06 with respect to displacements obtained from $\Delta'$ and $\Delta''$, respectively.

Our experiment result shows that the uncertainties for two wavelengths and for three wavelengths are almost the same. The displacement $\Delta$ can be obtained from either $\Delta'$ or $\Delta''$. If we measure both $\Delta'$ and $\Delta''$, the measurement becomes a redundant measurement, allowing us to improve the uncertainty in $\Delta$ by some algorithm. The air turbulence resulting the uncertainty in $\phi$ is the main error source in
the displacement measurement. If the uncertainty in phase measurement of interference fringe is the same, the accuracy increases $K$-times by using the zooming method.

4. Conclusion
We propose a multi-wavelength heterodyne optical zooming method for nanometer measurement. The zooming factor $K$ can be adjusted easily according to different measurement accuracy, meanwhile using the same laser sources. Moreover, the heterodyne technique ensures the displacement measurement with high signal to noise ratio, and measurement redundancy improves the uncertainty. The uncertainty in our optical zooming method is about 4 nm.

Acknowledgments
This work is supported by National Nature Science Foundation of China (Grant No. 50375084). The authors would like to thank Mr. K. Wang for his kind help in experiment

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