

Article ID 1004-924X(2003)01-0098-06

Heterodyne testing technique and its applications in micro-machining

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Abstract : Two main problems of heterodyne interferometer , lateral resolution of interferometer , and the nonlinear errors and its compensation , are discussed by first introducing a new analytical method to achieve positioning accuracy of sub-micron and then establishing a mathematical model of the relationship between the measurement phase and the amplitude distribution of laser beam to explain the gradual change of the measurement phase around the sharp step. The amplitude distribution of laser beam at the step can be got and the lateral positioning accuracy can be achieved to the magnitude of submicron by using the estimation method used for ordinary laser beam. The results of analysis of the three major nonlinear error sources of the common-path interferometer show that the error caused by Wollaston prism is mainly second harmonic and the error caused by elliptical polarization of laser is first harmonic. Further analysis indicates that the misorientation of metal mirror can cause the two reflecting beams to change from linear polarized beams into elliptical polarized beams with nonorthogonal and nonequal eccentricity , which can generate mainly the first harmonic nonlinear error. In additions , error compensation methods are also proposed to improve the accuracy of the interferometer.

Key words : heterodyne interferometer ; positioning accuracy ; nonlinear error ; polarization mixing

CLC number : TH741.13 **Document code :** A

1 Introduction

Micromachining plays an important role in MEMS and microelectronic industry. To assure the product quality of micromachining , advanced testing techniques with nanometer accuracy become the key to the manufacturing. In the past few years , heterodyne interferometer , especially the common-path heterodyne interferometer was paid much attention to and was assumed suitable for measuring

3D structures of micromachined parts. Because the measured parts and the reference beams are in the same environment , the interferometer is free of air turbulence , temperature variance and mechanical vibration along the direction of measurement so that the need for the environment is largely reduced^[1-2]. To improve the performance of heterodyne interferometer , two main problems need to be further studied: the first is the lateral resolution of the interferometer and the second is the nonlinear error and its compensation methods.

Received date : 2002-10-05 ; **Revised date :** 2002-11-20.

Foundation item : This work is funded by the Defence Foundation of China (Project No. 98J18.3.3HK0119)

Typically the lateral resolution of the interferometer is limited by the diameter of laser beam (usually $2 \sim 4 \mu\text{m}$), which influences the lateral positioning accuracy of a microstructure^[3]. However the method of reducing the beam diameter to improve the lateral resolution has its limitations^[4]: (1) According to the theory of diffraction, the minimum diameter of laser beam is about $1 \mu\text{m}$. That means the lateral resolution of heterodyne interferometer is no more than $1 \mu\text{m}$; (2) the optical system with small focus waist has small depth of field too, which makes the optical system difficult to find the accurate focal position; (3) The moving table with small step interval and stability in the heterodyne interferometric system is difficult to make and the price is high. Therefore, new methods should be studied to improve the lateral resolution without raising the price of the system.

Nonlinear errors are the main error sources in the heterodyne interferometer, which can sometimes achieve several nanometers. The error may be first-or second-harmonic, which is caused mainly by the polarization mixing (or frequency mixing) of the two measurement beams with different frequency and polarization^[5]. In recent years, the error sources and the compensation methods are studied by many researchers. In 1990, Bobroff^[6] et al. theoretically analyzed the nonlinear error by non-orthogonality of the linear polarization beams from laser and the effect of the ellipticity of input beams. He theoretically explained the first-order non-linearity and introduced the amplitude modulation method to compensate the periodic errors. Freitas and Player^[7] further explained the second harmonic component of error with Jones Matrix and found that rotational misalignment of orthogonal input states relative to the polarizing beam splitter axes might produce second harmonic errors and the values might increase substantially as the angular misalignment increased. Park^[8] discussed the polarization properties of solid-state cube-corners in common use and concluded that the axial orientation of the uncoated corner reflector had an effect

on the strength of the beat signal and the non-linearity error. Bin Li^[9] studied the phase fluctuation in dual-wavelength heterodyne interferometer and found the first and second harmonic errors caused by EOM prism. Moreover, some new error compensation methods^[10-11] have been studied recently. For example, Shen presented a novel interferometer with cat reflectors and two photodetectors to measure two measurement signals, and Badami used frequency domain method to separate the non-linearity of optical and electronic signal.

All above studies are focused on the Michelson interferometer. The errors caused by frequency mixing and elliptic polarization in common path heterodyne interferometer are rarely studied and some error sources in Michelson interferometer may have little effect on the common-path interferometer^[12].

In this paper, a new analytical method to achieve positioning accuracy of sub-micron is introduced at first. This method is easy to realize and the price of the working table is not high. The simulation results show that the lateral positioning accuracy of the interferometer is better than $0.1 \mu\text{m}$ with ordinary laser beam. On the other hand, the main error sources in common-path interferometer are also analyzed in this work. In particular, the nonlinear error caused by the reflection of metal mirror is specially studied in this paper, which was rarely studied before. The law of first- and second-harmonic errors is given and the compensation methods using the above equations are discussed.

2 Methods for improving the lateral positioning accuracy

Assume that w_0 is focal waist radius of laser beam and (x_0, y_0) are the central coordinate of the beam. Thus the normalized Gaussian distribution laser beam can be expressed as:

$$I(x_i) = \frac{I(x_i)}{I(x_0)} = \exp[-2(x - x_0)^2/w_0^2] \quad (1)$$

Take the heterodyne interferometer with Wollaston prism for example^[13-14]. When the two measurement beams scan the step at the position shown in

$$\tan(x_i) = \frac{[Q_1 \times (1 - I(x_i))] \times \sin(D_1) + Q_2 \times I(x_i) \times \sin(D_2)}{[Q_1 \times (1 - I(x_i))] \times \cos(D_1) + Q_2 \times I(x_i) \times \cos(D_2)}, \quad (2)$$

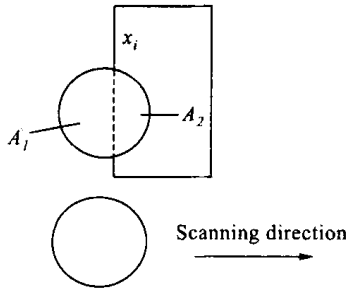


Fig. 1 Scanning mode of the interferometer

Where D_1 is the phase difference between the beams both on the base and D_2 is the phase difference between beams with one on the base while the other being on the step. Q_1 and Q_2 are the reflectance index of the base and the step respectively. The normalized amplitude distribution $I(x_i)$ can be calculated from Eq. 2 if the phase difference $M(x_i)$ at position x_i is measured. Because $I(x_i)$ conforms to standard normal distribution too. Comparing Eq. 1 with standard normal distribution $F(z) = \int_{-\infty}^z e^{-x^2/2} dx$, we can see that the leading difference between $F(z)$ and $I(x_i)$ is on the phase of the two functions. In order to transfer $I(x_i)$ got from Eq. 2 into standard normal distribution, the following phase transition must be made:

$$z^2/2 = 2(x - x_0)^2, \quad (3)$$

Further the following equation can be got:

$$x = \frac{z}{\sqrt{2}} + x_0, \quad (4)$$

where x_0 is the position of the step, r is the radius of the laser beam and z is the lateral coordinate

Fig. 1, the phase difference $M(x_i)$ of heterodyne interferometric signal is:

of standard normal distribution when $I(x_i)$ and $F(z)$ are equal. With enough known x and z , x_0 and r can be accurately estimated with nonequal interval regression method and the random errors are reduced. The simulation is made with standard normal distribution assuming that the measurement accuracy of x_i is magnitude of $0.01 \mu\text{m}$. The results show that the estimation value of step position is 0.0023 with ideal value being 0.00 and the diameter of laser beam is 1.3987 with the ideal value 1.414 . The error of estimation is 0.0023 and -0.0164 , respectively.

3 Nonlinear errors of the heterodyne interferometer

The two measurement beams in the heterodyne interferometer should be linear polarized beams with the polarization directions orthogonal. But in actual systems, polarization mixing (or frequency mixing) may occur, which can cause measurement errors. The heterodyne interference signal with polarization mixing can be expressed as:

$$(s, \varphi) = (1, \varphi_m) + \left(\frac{A}{|A|}, \varphi_A - \varphi_B\right) + \left(\frac{A}{|B|}, \varphi_A - \varphi_B\right) + \left(\frac{A}{|A|} \times \frac{A}{|B|}, \varphi_A - \varphi_B\right), \quad (5)$$

Where s and φ are the amplitude and phase of the measurement beat signal, respectively. φ_m is the ideal phase difference, A , B , φ_A , and φ_B are the amplitudes and phase jumps of the mixing beams. The main error sources in the heterodyne interferometer with Wollaston Prism are the misorientation of Wollaston Prism, elliptic polarization of laser beam and the reflection of metal mirror.

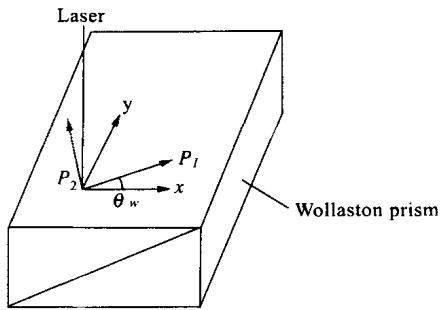


Fig. 2 Misorientation of incidence beam relative to the wollaston prism

The installation error of Wollaston Prism is shown in Fig. 2 with misorientation error θ_w . Because the polarization direction of incident beam is not parallel to the crystal axis of the prism, the output signal may be polarization mixed as (A and B are incident beam)

$$\begin{cases}
 A = |E_1| \cos \theta_w e^{i(2f_1 + \theta_w)} \\
 \quad = |E_2| \sin \theta_w e^{i(2f_2 + \theta_w)} \\
 B = |E_2| (1 - \cos \theta_w) e^{i2f_2} \\
 \quad = |E_1| (1 - \sin \theta_w) e^{i2f_1}
 \end{cases}$$

Take A and B into Eq. (5), we can calculate the first- and second- harmonic errors of the interference signals as and

$$\begin{cases}
 s = 2 \tan \theta_w \sin \theta_w \quad \text{and} \\
 s = 2 \tan \theta_w \cos \theta_w \\
 s = \tan^2 \theta_w \cos^2 \theta_w \quad \text{represents the amplitude} \\
 \tan^2 \theta_w \sin^2 \theta_w
 \end{cases}$$

attenuation index during the propagation of the two beams. Because the two measurement beams are propagate together, θ_w can be set to zero and only second harmonic error exists. The maximum value of the error is $\pm \tan^2 \theta_w$.

Because the laser is Zeeman stabilized, the output beam from the $\lambda/4$ plate is elliptic polarization mode. Assume that the major axis of the ellipses are 1 and the minor axis of the ellipses are e_1 and e_2 , respectively. Therefore the two beams with nonorthogonal angle θ_l can be expressed as Eq. (6) :

$$\begin{aligned}
 E_1 &= |E_1| \times e^{i2f_1} (y + e_1 \times e^{-\frac{\theta_l}{2}} x) \\
 E_2 &= |E_2| \times e^{i2f_2} \left[\begin{aligned}
 &\left[e_2 \times \cos \theta_l \times e^{-\frac{\theta_l}{2}} + \sin \theta_l \right] y + \\
 &\left[-e_2 \times \sin \theta_l \times e^{-\frac{\theta_l}{2}} + \cos \theta_l \right] x
 \end{aligned} \right]
 \end{aligned}
 \tag{6}$$

Take the polarization mixing parts from Eq. (6) into Eq. (5), the first-order measurement error is concluded as :

$$\begin{cases}
 r = - (e_2 - e_1) \cdot \cos \theta_l - \tan \theta_l \cdot \sin \theta_m \\
 s = - (e_2 - e_1) \cdot \sin \theta_m + \tan \theta_l \cdot \cos \theta_m
 \end{cases}
 \tag{7}$$

In actual system, almost all laser beams have eccentricity (e) and non-orthogonal angle (θ_l). The maximum value of this two parameters are around 0.015 ~ 0.04 and 1° . If $e = 0.04$, $\theta_l = 1^\circ$, then $\theta_m = 2.488^\circ$, the error caused by the elliptic polarization is 2.2 nm.

It is requested theoretically in the heterodyne interferometer that the two linearly polarized incident beams are orthogonal with one parallel to the normal plane of the reflector. Although amplitude reflectivity r_s, r_p and phase jump δ_s, δ_p in the reflecting beam change, $\delta_s - \delta_p$ is constant during measurement and the polarization plane of the reflecting beam don't change so that no frequency mixing and non-linear error occur. But in actual system, the mis-orientation error (θ_l) make every incident linear polarization beam decompose into P and s part to make the reflecting beam become elliptic polarized beam with orientation of the two ellipses having non-orthogonal and non-equal eccentricity. Fig. 3 shows mis-orientation of incidence beam E_1 and E_2 with frequency f_1 and f_2 . Axis x is in the normal plane of the mirror and is parallel to P part. Axis y is vertical to the normal plane of

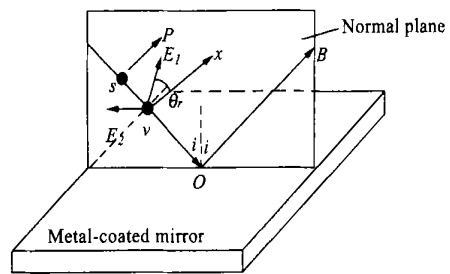


Fig. 3 Misorientation of incidence beam relative to the metal-coated mirror

the mirror and is parallel to s part. Assumed that $E_1 = E_2 = E$. The P and s components in the in-

idence beam are : $E_{1p} = E \cdot \cos \theta_r$, $E_{1s} = E \cdot \sin \theta_r$ ($\theta_r = 0$) and $E_{2p} = E \cdot \sin \theta_r$, $E_{2s} = E \cdot \cos \theta_r$ (with $\theta_r = \theta$) , where θ is the phase difference between s and P components.

After reflecting from the mirror , the beams E_1 and E_2 have changed into $E_{1'}$ and $E_{2'}$, which can be expressed as : $E_{1'} : p : a_{1x} = E \cdot \cos \theta_r \cdot \rho$, $s : a_{1y} = E \cdot \sin \theta_r \cdot s$. $E_{2'} : p : a_{2x} = E \cdot \sin \theta_r \cdot \rho$, $s : a_{2y} = E \cdot \cos \theta_r \cdot s$ and θ changed into θ' . Therefore , $E_{1'}$ and $E_{2'}$ have become elliptic polarization light . After coordinate translation , the major and minor axis of ellipse and the mis-orientation angles of major axis of $E_{1'}$ and $E_{2'}$ relative to x and y axis can be calculated , respectively . If the reflector is aluminum , $N = 1.39$, $K = 7.56$, $i = 45^\circ$ (i is incident angle) , $\theta_r = 1^\circ$, it is calculated that non-orthogonal error of $E_{1'}$ and $E_{2'}$ is $\theta' = \theta - \theta_2 = 0.062^\circ$ and the eccentricity of the two ellipses is : $e = \frac{a_{1y}}{a_{1x}} - \frac{a_{2y}}{a_{2x}} = 0.002$. And θ' and e increase when θ_r becomes larger .

When $E_{1'}$ and $E_{2'}$ come into Wollaston prism , the reflecting beams can be expressed as :

$$\begin{cases} \tilde{E}_1 = | E | \cdot e^{2if_1} [(e_1 \cdot \cos \theta_1 \cdot e^{-i\sqrt{2}} + \sin \theta_1) \tilde{y} + (-e_1 \cdot \sin \theta_1 \cdot e^{-i\sqrt{2}} + \cos \theta_1) \tilde{x}] \\ \tilde{E}_2 = | E | \cdot e^{2if_2} [(e_2 \sin \theta_2 \cdot e^{-i\sqrt{2}} + \cos \theta_2) \tilde{y} + (-e_2 \cdot \cos \theta_2 \cdot e^{-i\sqrt{2}} - \sin \theta_2) \tilde{x}] \end{cases} \quad (8)$$

Take the polarization mixing parts from Eq. (8) into Eq. (5) , the first-order phase and amplitude error are :

$$\begin{cases} \theta_m = \theta - \theta_m = (e_1 - e_2) \cdot \cos \theta_m + (\tan \theta_1 - \tan \theta_2) \cdot \sin \theta_m \\ s = s - 1 = (e_1 - e_2) \cdot \sin \theta_m + (\tan \theta_1 - \tan \theta_2) \cdot \cos \theta_m \end{cases} \quad (9)$$

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From above discussion , it is concluded that in the installation of the interferometer , laser with small non-orthogonality and eccentricity is selected and $\lambda/4$ plate should have small phase retardation . Besides , in order to reduce frequency mixing , the polarization direction of the linear polarized beam should parallel (or vertical) to the normal plane of the metal-coated mirror and furthermore , this normal plane should parallel to the crystal axis of Wollaston prism . Also , the compound phase error $\theta_c(s_c)$ and θ_c are all functions of measured phase θ_m) can be calculated using the above equations . s_c can be got by the amplitude photodetector by method in reference^[12] , thus θ_c can be calculated and the measurement phase can be compensated point by point to achieve higher accuracy .

4 Conclusion

A mathematical model is set up to explain the gradual change of the heterodyne interference phase difference around the sharp step . And the regression techniques are used to successfully improve the lateral positioning accuracy of common-path heterodyne interferometer to sub-micron magnitude with ordinary laser beam . In addition , the three main sources of nonlinear error of interferometer are analyzed . They are all harmonic functions changing with the measurement phase θ_m . The maximum error caused by them is from several angstroms to several nanometers . To reduce the nonlinear error , the laser and other optical elements must be carefully selected and installation orientation must be correct . Besides , the error can also be compensated by the compound θ_c .

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适合于微细加工的外差探测技术及应用

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摘要:本文详细地讨论了外差干涉仪的两个主要问题,即干涉仪的横向定位问题和非线性误差分析及其误差补偿问题。首先,提出了一种新颖的解析方法实现干涉仪亚微米级的高精度定位。该方法首先建立了测量光束扫过台阶边缘时测量相位渐变数学模型,并讨论了它与激光束分布的关系。文章利用以上数学模型对测量相位数据进行了详细地分析,实现了在一般激光束径时,干涉仪的定位精度为亚微米量级。另一方面,文章详细地分析了共光路干涉仪三个主要误差源。分析结果表明:由 Wollaston 棱镜引起的误差主要是二阶误差,而由激光束的椭圆偏振化引起的误差为一阶误差。同时我们发现:金属反射镜的方位误差可以使线偏振光经反射后变为椭圆偏振光,该椭圆偏振光具有不正交性和不相等偏心率,文章首次详细地分析了这种不正交性和不相等偏心率与反射镜方位误差的关系及其由此产生的非线性误差。最后,文章分析了干涉仪的误差补偿措施以提高整个干涉仪的测量精度。

关键词:外差干涉仪; 定位精度; 非线性误差; 偏振混叠

中图分类号: TH741.13 **文献标识码:** A

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