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减小外差干涉一次谐波非线性误差的方法

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摘要: 为了补偿激光外差干涉纳米测量中的非线性误差, 提出了一种减小非线性误差的一次谐波方法。基于全反射理论分析了镀膜实体角锥棱镜反射光偏振特性, 并由此推导出角锥棱镜反射光偏振特性及测量角锥棱镜以其运动方向为轴线的轴向旋转对激光外差干涉非线性误差一次谐波的影响模型。理论分析表明, 测量角锥棱镜以其运动方向为轴线的轴向旋转会减小非线性误差一次谐波, 当测量角锥棱镜轴向旋转 97°时, 可使非线性误差一次谐波达到最小, 约为原有非线性误差一次谐波分量的 1/20 倍。当激光器出射的两束线偏振光存在 6°非正交误差时, 镀膜实体测量角锥棱镜轴向旋转角度从 0°增加到 97°, 非线性误差一次谐波由 5.30 nm 减小到 0.30 nm。

关键词: 光电子学; 外差干涉; 非线性误差; 角锥棱镜; 一次谐波

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Method to Reduce First Harmonic Nonlinearity in Laser Heterodyne Interferometry

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Abstract: To compensate of the nonlinearity error of heterodyne interferometers in nanometer measurement, a method for reducing the first harmonic nonlinearity is proposed. Based on the total reflection theory, polarization properties of coated corner-cube retroreflector are analyzed. Then, the effect on the first-harmonic nonlinearity by the polarization properties of reflected light of the cube-corner retroreflector and axial rotation in the motion direction of the measurement cube-corner retroreflector is derived. The simulation results show that the first harmonic nonlinearity is reduced by the axial rotation of the cube-corner retroreflector. When the axial rotation angle is 97°, the first harmonic nonlinearity is the smallest, which is about 0.05 times smaller than the original. When the nonorthogonal error of the two linearly polarized beams is 6°, and the axial orientation rotation angle increases from 0° to 97°, the first harmonic nonlinearity is reduced from 5.30 to 0.30 nm.

Key words: optoelectronics; heterodyne interference; nonlinear error; cube-corner retroreflector; first harmonic

1 引言

随着微电子、微机械及超精密加工的发展, 对位移测量精度的要求达到了纳米量级^[1]。激光外差干涉由于具有测量精度高、测量速度快、溯源性强等优点, 广泛应用于纳米测量, 但是其非线性误差的存在, 严重制约了激光外差干涉测量精度的进一步提

高^[2]。国内外许多学者对激光外差干涉非线性误差进行了深入的理论和实验研究, 以补偿非线性误差^[3~6]。Wenmei Hou 等^[3]提出的双相位检测方法可消除一次谐波非线性误差; V. G. Badami 等^[4]利用包含速率计和频谱仪的移动系统直接测量一次谐波和二次谐波非线性误差的大小并进行补偿;

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Tae Bong Eom 等^[5]用锁相放大器对参考信号和测量信号的相位信号进行积分并进行椭圆拟和的方法补偿非线性误差。上述方法都能够在没有外部参考干涉仪的情况下补偿非线性误差,但电子系统或光路系统都很复杂。本文在研究镀膜实体角锥棱镜反射光偏振特性的基础上,提出了一种新的减小激光外差干涉非线性误差一次谐波的方法。在传统激光外差干涉仪位移测量光路中,将镀膜实体测量角锥棱镜安装在旋转台上,旋转台可以角锥棱镜运动方向为轴线轴向旋转,调整测量角锥棱镜轴向旋转角度为97°,然后开始外差干涉位移测量,实现了减小一次谐波非线性误差的目的,并进行仿真验证。

2 角锥棱镜反射光偏振特性分析

由于角锥棱镜具有逆向反射特性,便于安装、调试和测量,因此是激光外差干涉测量系统的主要光学元件,并具有特殊的偏振特性。

2.1 全反射理论

如果光从折射率为 n_1 的介质入射到折射率为 n_2 的介质($n_2 < n_1$),入射角大于临界角时发生全反射。如图1所示分界面法线向量为 \mathbf{M} ,入射波矢量 \mathbf{k} ,则入射光波电场为 $E = E_s \mathbf{s} + E_p \mathbf{p}$, $\mathbf{s} = \mathbf{k} \times \mathbf{M}$ 是垂直入射面的单位向量, $\mathbf{p} = \mathbf{k} \times \mathbf{s}$ 是垂直 \mathbf{k} 和 \mathbf{s} 所在平面的单位向量。根据反射定律可知反射光波矢量 $\mathbf{k}' = \mathbf{k} - 2(\mathbf{k} \cdot \mathbf{M})\mathbf{M}$,由麦克斯韦方程及其边界条件可知反射光波电场为 $E' = E_s r_s \mathbf{s}' + E_p r_p \mathbf{p}'$,其中反射率^[7]

$$r_s = \frac{\cos \theta - (n^2 - \sin^2 \theta)^{1/2}}{\cos \theta + (n^2 - \sin^2 \theta)^{1/2}}, \quad (1)$$

$$r_p = \frac{n^2 \cos \theta - (n^2 - \sin^2 \theta)^{1/2}}{n^2 \cos \theta + (n^2 - \sin^2 \theta)^{1/2}}, \quad (2)$$

对于镀膜实体角锥棱镜,(1)式、(2)式中 θ 为入射角, $\cos \theta = -\mathbf{k} \cdot \mathbf{M}$,入射介质 n_1 为玻璃,折射介质是金属,具有复折射率 $\tilde{n}_2 = N - iK$, $n = \tilde{n}_2/n_1$,反射率 r_s, r_p 为复数^[8]。

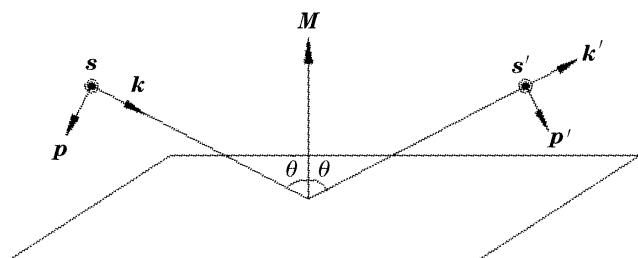


图1 光在界面处的全反射

Fig. 1 Total reflection of light at the interface

2.2 角锥棱镜反射光偏振特性分析

如图2所示为角锥棱镜光路图, O' 点为角锥棱镜基面中心点,以角锥棱镜的角点 O 点为原点,以其三条直角棱边 OA, OB, OC 为坐标轴建立坐标系 xyz 。令入射光垂直角锥棱镜基面入射,其波矢量 $\mathbf{k}_0 = (1/\sqrt{3})[-1, -1, -1]$,入射光波电场 $E_0 = as + bp$, $a^* a + b^* b = 1$,则经角锥棱镜三个直角面反射后,根据全反射理论,并假定所有反射面的反射率相同,由角锥棱镜基面反射的光波电场为^[9,10]

$$E = (c_{11}a + c_{12}b)\mathbf{s}' + (c_{21}a + c_{22}b)\mathbf{p}', \quad (3)$$

其中 $\mathbf{s}' = \mathbf{s}, \mathbf{p}' = -\mathbf{p}, c_{11}, c_{12}, c_{21}, c_{22}$ 均为系数,表示光波经镀膜角锥棱镜反射后,s,p 分量的振幅和相位的变化,且有

$$c_{11} = (r_s^3 + 6r_p r_s^2 - 3r_s r_p^2)/8, \quad (4)$$

$$c_{12} = \sqrt{3}r_p(r_s + r_p)/8, \quad (5)$$

$$c_{21} = -\sqrt{3}r_s(r_s + r_p)/8, \quad (6)$$

$$c_{22} = (r_p^3 + 6r_p^2 r_s - 3r_p r_s^2)/8, \quad (7)$$

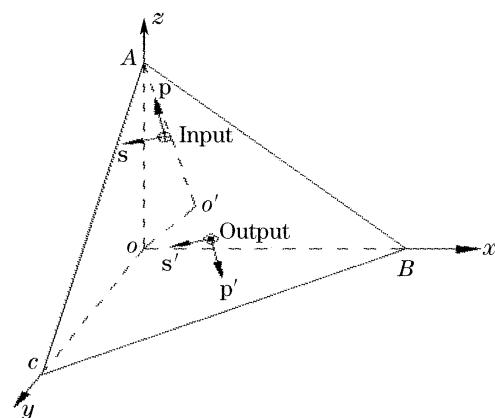


图2 角锥棱镜光路图

Fig. 2 Incident beam of cube-corner retroreflector

在激光外差干涉仪中,入射到角锥棱镜基面的光为线偏振光,且入射光垂直基面入射。设测量角锥棱镜在放置时,其一条直角棱边在基面的投影垂直测量角锥棱镜的运动方向,且与测量系统Z轴平行,当入射光为p光,角锥棱镜以 OO' 为轴线轴向旋转角度 γ ,即p光偏振面相对入射面旋转了 γ ,则角锥棱镜反射光波电场为

$$E = (c_{11} \sin \gamma + c_{12} \cos \gamma)\mathbf{s}' + (c_{21} \sin \gamma + c_{22} \cos \gamma)\mathbf{p}', \quad (8)$$

由(8)式可以看出,由于角锥棱镜表面镀金属膜,当线偏振光入射到角锥棱镜时,其反射光变为椭圆偏振光,且角锥棱镜的轴向旋转会改变反射光的偏振特性。

3 非线性误差一次谐波的减小方法

3.1 角锥棱镜偏振特性对激光外差干涉测量信号的影响

理想激光外差干涉测量系统如图3所示,设激光器发出的两束频率相差很小、振动方向正交的线偏振光的振动方程分别为

$$\mathbf{E}_1 = i \cos(2\pi f_1 t), \quad (9)$$

$$\mathbf{E}_2 = j \cos(2\pi f_2 t), \quad (10)$$

其中*i*和*j*分别为激光器出射平行分量*s*,垂直分量*p*的偏振光偏振方向矢量,*f*₁,*f*₂分别为*s*,*p*偏振光的频率。

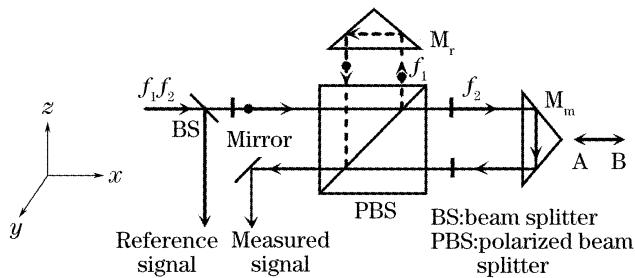


图3 激光外差干涉测量原理图

Fig. 3 Schematic diagram of heterodyne interferometric measurement

考虑镀膜实体角锥棱镜偏振特性的影响时,两束线偏振光经偏振分束器(PBS)反射和透射后,分别由镀膜实体参考角锥棱镜M_r和镀膜实体测量角锥棱镜M_m反射后变为

$$\begin{aligned} \mathbf{E}'_1 &= i c_{11} E_0 \cos(2\pi f_1 t + \phi_1) + \\ &\quad j c_{21} E_0 \cos(2\pi f_1 t + \phi_1), \end{aligned} \quad (11)$$

$$\begin{aligned} \mathbf{E}'_2 &= i c_{12} E_0 \cos(2\pi f_2 t + \phi_2) + \\ &\quad j c_{22} E_0 \cos(2\pi f_2 t + \phi_2), \end{aligned} \quad (12)$$

其中 ϕ_1 为参考光路相位增量, ϕ_2 为测量光路相位增量。两束被角锥棱镜反射的光再次经偏振分束器和

检偏器后,形成拍频信号

$$\begin{aligned} E_m &= c_{11} E_0 \cos(2\pi f_1 t + \phi_1) + \\ &\quad c_{22} E_0 \cos(2\pi f_2 t + \phi_2), \end{aligned} \quad (13)$$

则光电接收器接收到的测量信号为

$$\begin{aligned} I_m &\propto |c_{11}| |\exp(i\delta_{11}) E_0 \exp[i(2\pi f_1 t + \phi_1)]| + \\ &\quad |c_{22}| |\exp(i\delta_{22}) E_0 \exp[i(2\pi f_2 t + \phi_2)]|^2 \propto \\ &\quad I_0 |c_{11}| |c_{22}| \cos[2\pi \Delta f t + \Delta\phi + \delta_{22} - \delta_{11}], \end{aligned} \quad (14)$$

其中($|c_{11}|, \delta_{11}$)和($|c_{22}|, \delta_{22}$)分别为 c_{11} 和 c_{22} 的振幅和相位, $I_0 = 2E_0^2$, $\Delta f = f_2 - f_1$. $\Delta\phi = \phi_2 - \phi_1$ 包含了被测位移信息。对于给定的镀膜实体角锥棱镜,其反射率一定,根据(4)式~(7)式知 c_{11} 和 c_{22} 的振幅和相位为定值。因此从(14)式可以看出,角锥棱镜反射光的偏振椭圆化并没有引入非线性误差,只是减小了测量信号的强度。

3.2 一次谐波非线性误差的减小方法

由于激光腔存在双折射和二色性,激光器发出的两束偏振光存在非正交和椭圆偏振现象,文献[3]指出激光束的偏振非正交和椭圆化引起的非线性误差为半波长的一次谐波。

为了简化分析,只考虑激光束的偏振非正交引入的一次谐波非线性误差。假定频率为*f*₁的*s*偏振光偏离正交方向角度为 α ,镀膜实体测量角锥棱镜M_m安装在旋转台上,且它在外差干涉仪光路中放置时光束垂直其基面入射。M_m的一条直角棱边在其基面的投影垂直其运动方向AB,并与Z轴平行,如图3所示。旋转台以测量角锥棱镜M_m运动方向AB为轴线轴向旋转它们的角度为 γ ,则存在偏振非正交的两束线偏振光如(9)式和(10)式。它们经偏振分束器分光后分别由M_r和M_m反射,再次经偏振分束器后由检偏器检偏形成拍频信号为

$$E'_m = c_{11} \cos \alpha \cos(2\pi f_1 t + \phi_1) + (c_{21} \sin \gamma + c_{22} \cos \gamma) \times [\cos(2\pi f_2 t + \phi_2) + \sin \alpha \cos(2\pi f_1 t + \phi_2)], \quad (15)$$

则光电接收器接收到的测量信号光强为

$$\begin{aligned} I_m &\approx |c_{11}| \cos \alpha \exp(i(2\pi f_1 t + \delta_{11} + \phi_1)) + (|c_{21}| \exp(i\delta_{21}) \sin \gamma + |c_{22}| \exp(i\delta_{22}) \cos \gamma) \times \\ &\quad [\exp(i(2\pi f_2 t + \phi_2)) + \sin \alpha \exp(i(2\pi f_1 t + \phi_2))]^2 = I_0 A^* \cos(2\pi \Delta f t + \Delta\phi + \Delta\phi_n), \end{aligned} \quad (16)$$

式中($|c_{21}|, \delta_{21}$)为 c_{21} 的振幅和相位, $\Delta\phi_n$ 为镀膜实体角锥棱镜反射光偏振特性及测量角锥棱镜以其运动方向为轴线的轴向旋转对一次谐波非线性误差的影响

$$\Delta\phi_n = -\arctan \left[\frac{A \cos \alpha + B \sin \alpha \sin(\Delta\phi)}{C \cos \alpha + B \sin \alpha \cos(\Delta\phi)} \right], \quad (17)$$

其中

$$A = |c_{11}| |c_{21}| \sin \gamma \sin(\delta_{11} - \delta_{21}) + |c_{11}| |c_{22}| \cos \gamma \sin(\delta_{11} - \delta_{22}), \quad (18)$$

$$B = |c_{21}|^2 \sin^2 \gamma + |c_{22}|^2 \cos^2 \gamma + 2 |c_{21}| |c_{22}| \sin \gamma \cos \gamma \cos(\delta_{22} - \delta_{21}), \quad (19)$$

$$C = |c_{11}| |c_{21}| \sin \gamma \cos(\delta_{11} - \delta_{21}) + |c_{11}| |c_{22}| \cos \gamma \cos(\delta_{11} - \delta_{22}), \quad (20)$$

(17) 式非线性误差的相位大小 $\Delta\phi_n$ 对应的测量位移大小为

$$\Delta l_n = \Delta\phi_n \cdot \lambda / (4\pi), \quad (21)$$

其中, λ 为光波波长。

为了分析镀膜实体角锥棱镜反射光偏振特性及测量角锥棱镜以其运动方向为轴线的轴向旋转对激光外差干涉一次谐波非线性误差的影响, 设角锥棱镜表面镀金属银, 其复折射率为 $0.067 - i4.05^{[11]}$, 实体角锥棱镜采用 BK7 玻璃制作。当激光器出射光束存在偏振非正交误差 α 时, 根据(17)式计算的测量角锥棱镜不同轴向旋转角度下引起的非线性误差仿真曲线如图 4 所示。图 4 中曲线 1, 2, 3 对应的激光束偏振非正交误差 α 分别为 $3^\circ, 6^\circ, 9^\circ$ 。当测量角锥棱镜轴向旋转角度 $\gamma=0^\circ$ 时, α 分别为 $3^\circ, 6^\circ, 9^\circ$ 对应的外差干涉测量一次谐波非线性误差分量分别为 $2.64 \text{ nm}, 5.30 \text{ nm}, 8.00 \text{ nm}$, 当 $\gamma=97^\circ$ 时, α 分别为 $3^\circ, 6^\circ, 9^\circ$ 对应的外差干涉一次谐波非线性误差分别为 $0.13 \text{ nm}, 0.26 \text{ nm}, 0.39 \text{ nm}$ 。由图 4 可以看出, 测量角锥棱镜以运动方向为轴线的轴向旋转可以减小外差干涉一次谐波非线性误差, 无论激光束偏振非正交误差 α 大小如何, 当测量角锥棱镜轴向旋转角度为 97° 时, 一次谐波非线性误差都达到最小, 约为原有一次谐波非线性误差的 $1/20$ 倍。因此, 在激光外差干涉测量之前, 将镀膜实体测量角锥棱镜的旋转角度调整好且为 97° , 然后进行动态位移测量, 可以实现减小一次谐波分量的非线性误差, 进而提高测量精度。

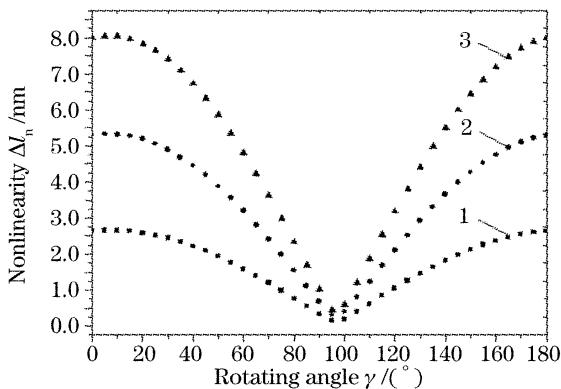


图 4 不同 α 时测量角锥棱镜轴向旋转对一次谐波非线性误差的影响

Fig. 4 Influence of axial orientation rotation to measure cube-corner retro reflector on first-harmonic nonlinearity at different α

4 结 论

提出了一种新的减小激光外差干涉一次谐波非

线性误差的方法。通过分析镀膜实体角锥棱镜反射光的偏振特性, 建立了角锥棱镜偏振特性及其轴向旋转对一次谐波非线性误差的影响模型。将测量角锥棱镜安装在旋转台上, 旋转台可顺时针或逆时针以测量角锥棱镜运动方向为轴线轴向旋转, 在外差干涉系统测量之前, 轴向旋转测量角锥棱镜的角度为 97° , 之后开始位移测量, 即可实现减小一次谐波非线性误差影响的目的。当激光束偏振非正交角度为 6° 时, 镀膜实体测量角锥棱镜以运动方向为轴线的轴向旋转角度从 0° 增加到 97° , 一次谐波非线性误差由 5.30 nm 减小到 0.30 nm 。该方法避免了现有的非线性误差补偿方法光路系统和电路系统复杂的缺点, 系统实现简单。

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