基于平面反射式全息光栅的激光自混合纳米位移测量研究

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摘　要：纳米位移测量技术是实现高精度纳米制造的基础。激光自混合干涉为精密纳米位移测量提供了一种结构简便、成本低廉，同时测量精度可达纳米量级的精密位移测量方法。区别于传统基于反射镜或散射面为反馈元件的激光自混合干涉测量方案，研究了一种基于平面反射式全息光栅的激光自混合纳米位移测量方法，该方法的位移测量结果以光栅的周期为基准。实验测得了在弱反馈强度条件下的光栅自混合干涉信号，通过阈值设定的方法确定位移方向的反转点，结合反余弦的相位解包裹算法处理光栅自混合信号，获得了对应的位移测量值。最终采用商用激光干涉仪与自组装的光栅自混合干涉仪进行位移测量数据的比对测量，实验结果表明，经过线性修正后，其位移误差不超过 0.241%。

关键词：纳米位移测量；　激光自混合；　光栅干涉仪；　全息光栅

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0　引　言

纳米位移测量技术是实现高精度纳米制造的基础，激光干涉仪[1]、光栅干涉仪[2] 等较为传统的纳米位移测量方法需要诸如反射镜、分束器、波片等外设光学元件。相比于这些传统的双光束干涉测量方法，激光自混合干涉仪的光干涉信号可由集成在光电二极管后方的光电探测器采集，因此实现了一种结构简单、成本低廉的精密位移测量方法。

激光自混合干涉又称为激光回馈干涉，是一种基于外腔光反馈原理[3]，在激光器谐振腔内部形成光干涉效应的精密位移测量方法。激光自混合干涉测量技术主要包含三个核心部分：光源、外腔反馈元件、信号处理单元。激光自混合测量技术自发明以来，已广泛应用于包括位移测量[4]、振动测量[5]、速度测量[6]、激光二极管参数估计[7]、光学加密技术[8]、血液流速测量[9] 等领域，已在不同的光源系统中实现并得到了应用，比如在 He-Ne 激光器系统中实现了对于液晶双折射现象的测量[10]，在正交偏振光源中实现了远距离的振动测量[11]，运用 Nd:YAG 激光对压电陶瓷的电压响应情况进行测量[12]，在垂直腔面发射半导体激光器中实现了对于不同散射表面的自混合测速[13]。

激光自混合测量的外腔反馈元件主要有三种：反射镜[14]、散射表面[15]、光栅[16]。大多数激光自混合测量方案以反射镜作为外腔反馈元件。对于散射表面作为外腔反馈元件的研究，则扩展了自混合测量在一般场景中的应用能力。与基于反射镜或者散射面作为外腔反馈元件不同的是，以光栅为外腔反馈元件的激光自混合方案的测量基准为光栅周期而非激光波长，这将进一步提高自混合测量系统的抗环境干扰能力。近年来，基于光栅反馈的激光自混合测量的研究进展包括：基于反射式光栅反馈实现了 MEMS 加速度计的灵敏度测量[16]、基于光栅±1 级衍射光反馈的

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双光源激光自混合测量方案实现了分辨率小于 10 nm 的二维位移测量[17]，经过透射光栅二次衍射反馈信号的激光自混合方案实现了分辨率超越半光栅周期的位移测量[18] 等。

在激光自混合信号处理方面，主要研究如何提高自混合信号的重构精度，比如运用全相位谱分析方法将测量精度缩小至 4.4 nm[19]，采用相位调制与快速傅里叶变换算法相结合，提高了自混合测量的精度[20]。采用希尔伯特变换[21] 产生正交相位数据，从而可以通过求解反正切函数的相位解包裹算法来处理自混合干涉信号，生成对抗网络方法[22] 被用来还原含噪声的自混合信号。

为了探索基于光栅周期而非激光波长为测量基准的纳米位移测量方法，文中研究了基于平面反射式全息光栅反馈的激光自混合纳米位移测量方案，在信号处理方面，采用基于反余弦的相位解包裹方法，具体通过阈值设定的方法确定位移方向反转点，从而对反余弦相位进行正确的补偿，最终将实验处理得到的位移信号与商用激光干涉仪的位移测量值进行比对，来评估实验系统的误差。

1 实验原理与分析

1.1 实验设置

文中采用的基于平面反射式全息光栅的激光自混合纳米位移测量的实验装置如图 1 所示，源采用激光二极管光源 (Thorlabs, DL5146-101S)，中心波长为 405 nm，并且配备了温度控制和电流控制模块 (Arroyo-ment 5305) 以保证二极管稳定在单纵模输出。由激光二极管输出的激光经过一个非球面耦合透镜 (Thorlabs, C230TMD-A) 将输出激光聚焦到闪耀型的平面全息光栅表面产生衍射，入射角为利特罗角度θ，满足关系$\theta = \arcsin(\lambda/2d)$，其中$\lambda$是激光中心波长，$d$是光栅的周期。实验中采用的光栅是 2400 lp/mm 的平面衍射光栅，周期为 416.67 nm，故实验中利特罗角度为 27.08°。在利特罗入射角度下，由光栅产生的 1 阶衍射光的衍射角等于入射角，即 1 阶衍射光会沿着入射光原路返回到激光二极管内部，从而与激光二极管腔内部初始的激光光场发生自混合干涉，干涉形成的自混合光场会受到外腔的相位调制作用。光栅放置在一维直线电机纳米位移台上 (三英精控，ETSM-15G)，栅格方向与位移台方向保持一致，当位移台沿着光栅栅格方向运动时，会引起自混合光强的调制，从而可以实现纳米位移传感。在激光与光栅之间插入了二分之一波片和偏振分束器，将激光分束后由内置低噪声放大器的硅光电探测器 (Thorlabs, PDA10A2) 进行探测，从而将自混合的光功率信号转化为电压信号，经过数据采集卡采集后由计算机进行处理。

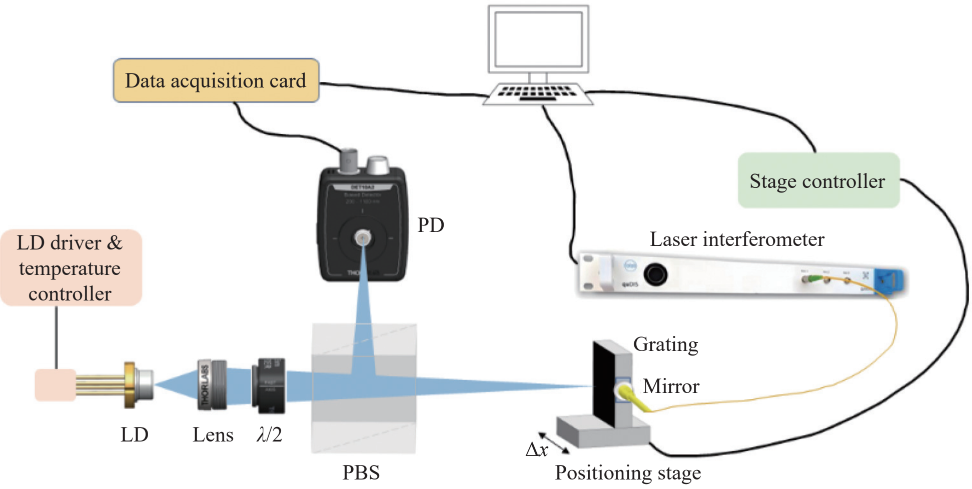

图 1 基于平面反射式全息衍射光栅的激光自混合纳米位移测量系统示意图

Fig.1 Schematic diagram of a laser self-mixing nano-displacement measurement system based on a planar reflective holographic diffraction grating

1.2 数据处理

激光自混合测量基于光反馈原理，严格的理论描述需要运用 Lang-Kobayashi 方程，通常采用三腔镜模型[3] 便于形象理解，如图 2 所示，在自混合测量中激

光二极管等效为一个由前后两个反射镜 M_1 和 M_2 以及之间的增益介质组成的线性腔结构。经 M_1 和 M_2 反射的二极管腔内基频光 E_1 与经过光栅衍射的 1 阶衍射光 E_2 在腔内发生自混合干涉形成总的电场 E，可表示为：

$$E = r_1 r_2 E_0 \exp(i2nkl) + r_1 t_2' r_g E_0 \times \exp(i(2nkl + 2kL + \varphi)) \tag{1}$$

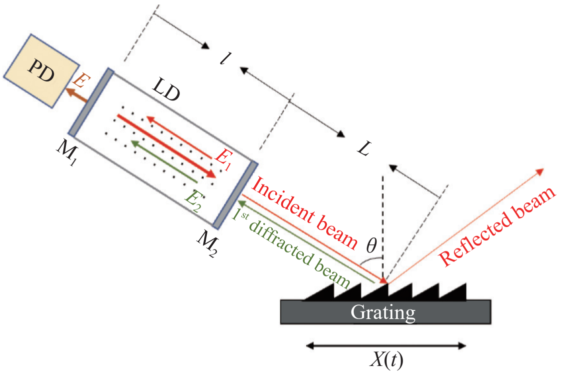

图 2 基于光栅反馈的激光自混合测量原理图

Fig.2 Schematic diagram of laser self-mixing measurement based on grating feedback

式中：r_1、r_2分别为 M_1 和 M_2 对基频光的反射率；t_2、t_2'分别为 M_2 对基频光和一阶衍射光的透射率；n 为二极管增益介质折射率；k 为基频光波矢；l 为二极管腔长；L 为外腔长度；φ为光栅运动引起的多普勒移频相位。在非相对论条件下，以利特罗角度入射产生的一阶衍射光反馈光的相移可表示为：

$$\varphi = 2\pi \Delta x / d \tag{2}$$

在稳态条件下激光自混合效应由频率方程和功率方程描述，其形式如下：

$$\begin{aligned} \omega_0 \tau &= \omega\tau + C \cdot \cos(\omega\tau - \arctan\alpha + \varphi) \\ P &= P_0 [1 + m P_{nor}] \\ P_{nor} &= \cos(\omega\tau + \varphi) \end{aligned} \tag{3}$$

式中：ω_0为无反馈条件下的基频光角频率；$\tau = 2L/c$；为激光在外腔中往返的时间；C 为反馈强度因子；α为线宽展宽因子；P 为激光器输出功率；P_0为无反馈条件下的激光初始输出功率；P_{nor}为归一化的自混合信号；m 为干涉条纹对比度。

为了分析弱反馈条件下的光栅自混合信号特征，对于自混合信号进行了仿真。基于激光二极管的参数范围，取$\alpha = 3$, $C = 0.2$, 光栅位移以正弦形式振动，得到的激光功率信号交流成分的仿真结果如图 3 所示。从图中可以看出，在弱反馈条件下 ($C < 1$)，光栅每运动一个光栅周期的距离时，光功率信号产生一个条纹信号，当运动速度变慢时，自混合信号条纹会变得稀疏。

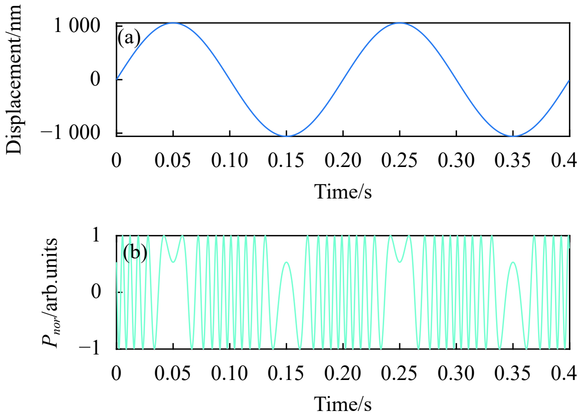

图 3 在正弦位移调制下，弱反馈时的光栅激光自混合信号仿真结果。(a) 光栅的位移信号$\Delta x = 1\,000\sin(10\pi t)$; (b) 归一化的光功率信号$P_{nor}$随时间变化的情况

Fig.3 Simulation results of laser self-mixing signal under sinusoidal displacement modulation and weak feedback condition. (a) Displacement signal of grating, where $\Delta x = 1\,000\sin(10\pi t)$; (b) Normalized optical power signal P_{nor} as a function of time

结合公式 (2) 和 (3) 可以看到，如果要获得位移信号Δx，关键要先从功率谱信号中重构出相位信号φ。P_{nor}是关于$\omega\tau + \varphi$的函数，$\omega\tau$是关于φ的周期函数，需要解公式 (2) 中的超越方程，为了简化位移重构计算，通常将$\omega\tau$作为一个误差项，并将$\omega\tau + \varphi$合并为一个总的相位φ_r，因此可以将P_{nor}看成是一个关于总相位φ_r的函数，满足：

$$P_{nor} = \cos(\varphi_r) \tag{4}$$

通过求解功率变化的反余弦函数可以得到的相位为：

$$\varphi_r = \arccos P_{nor} \tag{5}$$

由于反余弦函数的值域限制，包裹相位在 (0, π) 范围之间。想要获得实际相位，就要对相位进行一个解包裹处理，文中提出一个极大极小值检测法来进行相位展开，图 4 所示为经过反余弦计算后的包裹相位，先找出包裹相位的极大值、极小值点并读取其坐标位置，其中极大值用红“o”表示，极小值用黄“*”表示。

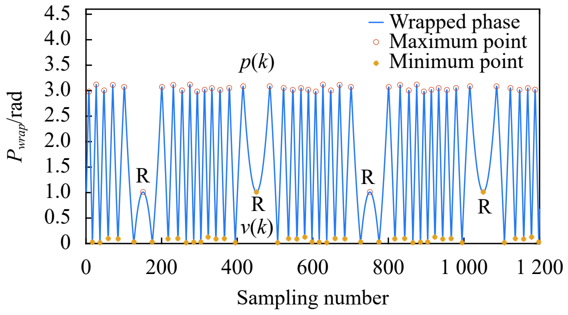

图 4 解包裹相位示意图

Fig.4 Diagram of unwrapping phase

在极大值、极小值中利用设定阈值的方法找出转折点 R，转折点即为光栅运动方向改变的点。在两个转折点之间的极大值点个数为 N，极大值点用$p(k)$表示，极小值点用$v(k)$表示，由于余弦函数在 $[0, 2\pi]$ 区间内不是单调函数，所以每经过一个极值点包裹相位φ_r的值要做加负处理，两个转折点之间的相位展开后可表示为：

$$\varphi_r = (-1)^n\varphi_{wrap} + (n-k-1)*2\pi \tag{6}$$

式中：φ_r表示展开后的相位；φ_{wrap}表示包裹相位；$k=(1,2,3\cdots N)$表示极值点的序号；$n=(0,1,2,3\cdots 2N)$表示每经过一个极值点 n 增加一个数值。每经过一个转折点，2π 的加减性会发生一次改变，即在下一段的两个转折点区间的相位展开结果为：

$$\varphi_r = (-1)^n\varphi_{wrap} - (n-k-1)*2\pi \tag{7}$$

1.3 实验结果

实验设置了位移台沿着光栅栅格方向以 1 mm/s，做单向行程为 10 μm 的往复的匀速直线运动时，根据如图 1 所示的基于平面衍射光栅的激光自混合实验系统，获得的自混合信号如图 5 所示。实际情况中，位移台为了在每一段位移的起点能保证以 1 mm/s 的初速度开始运动，会在每一段位移终止点附近通过 PID 振荡反馈来调节下一段位移起始点的初速度。

对于图 5 的自混合功率信号采用反余弦法可以求得图 6 的包裹相位图。图 6 中对于反余弦函数的相位值根据相位展开方法进行了加负处理，整体的结果都处于 $(-\pi, \pi)$ 之间。

基于图 6 的包裹相位数据，运用公式 (6) 和公式 (7) 可以获得解包裹相位，再运用公式 (2) 并代入光栅周期值可以获得相应的位移值，该实验采用的全息闪耀光栅周期为 416.67 nm，位移重构结果如图 7 所示。

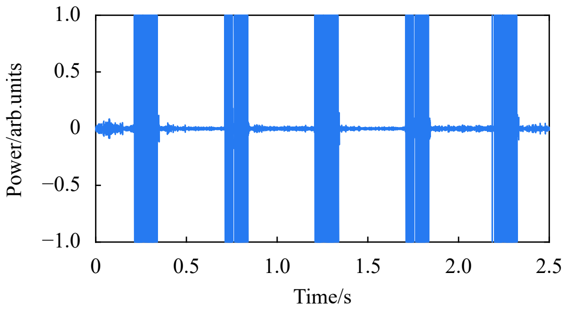

图 5 经过归一化后的基于平面反射式全息光栅的激光自混合信号(二极管工作电流为 40.6 mA，位移台设定为作 10 μm 振幅的匀速直线往复运动)

Fig.5 Normalized laser self-mixing signal based on the plane reflective holographic grating (The working current of laser diode is 40.6 mA, the displacement table makes a uniform linear reciprocating motion of 10 μm amplitude)

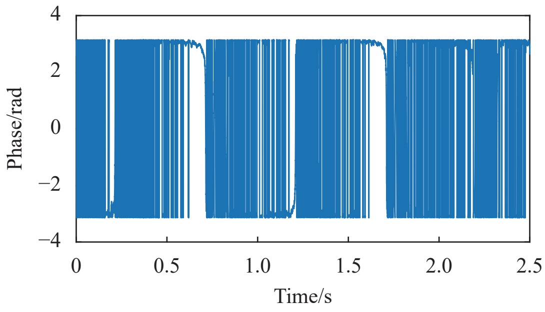

图 6 包裹相位图

Fig.6 Wrapped phase diagram

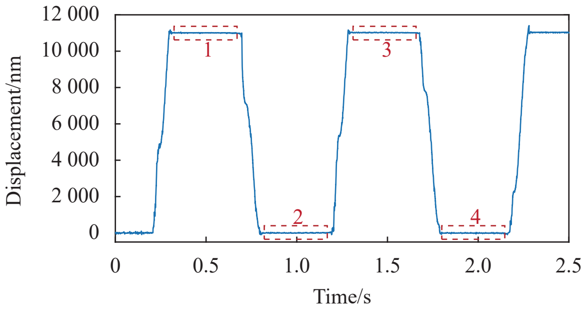

图 7 基于平面反射式全息光栅的激光自混合仪的位移重建结果

Fig.7 Displacement reconstruction result of laser self-mixing interferometer based on plane reflective holographic grating

从图 7 的位移重建结果可以看到，基于反余弦方法的光栅自混合位移测量结果还原了位移台的匀速直线运动的模式，每一次单向运动的位移振幅为 11 μm。为了验证光栅自混合位移测量值的重复性，基于图 7 的光栅自混合测量的位移重建结果，计算了

每一段行程的位移值。将位移测量结果的 4 个平台区域进行了标记，对应位移台在方向前的静止时间段，计算了每个区域的位移平均值和方差，结果如表 1 所示。相邻区域的平均位移值相减可以获得它们之间的位移台行程。数据结果表明，位移台单向行程值在 11.1029663 μm，比设定值 10 μm 稍大，这可能是由于光栅表面的不平整引入的散射噪声引起的。在位移静止区域有 5.8185 nm 的平均位移涨落，这主要是因采用的是光电流探测方法，无法排除系统的电子学噪声。

表 1 光栅激光自混合干涉仪位移均值和方差

Tab.1 Displacement mean and variance of grating laser self-mixing interferometer

Index	$\bar{x}$/nm	Δx_g/nm	$\sigma(x)$/nm
1	11 093.23	11 092.5014	4.7112
2	0.7286	−11 104.2314	5.8710
3	11 104.96	11 112.1661	3.4718
4	−7.2061	-	9.2199
Average value	-	11 102.9663	5.818475

为了修正光栅自混合位移重建的结果，实验中采用商用的激光干涉仪进行了位移比对校准。该商用激光干涉仪为德国 Qutools 公司的 QuDIS 型号的法布里珀罗干涉仪，其位移测量分辨率可以达到亚纳米量级。实验结果如图 8 所示，蓝色线条代表商用激光干涉仪位移测量结果，红色线条代表光栅自混合干涉仪位移重建信号，为了使得自混合信号与商用干涉仪信号匹配，将自混合信号整体除以了 1.1086 倍的线性偏差系数。结果表明，商用干涉仪的测量值与位移台设定值基本吻合，并且可以分辨出位移台在每一段位移终点处为了调整初速度而产生的振荡调整信号。对于图 8 的实验结果，分别计算了不同区域的商用激光干涉仪和修正后的光栅自混合测量的位移平均值和涨落，如表 2 所示。$\bar{x}$代表每一个区域的位移平均值，Δx_g代表光栅自混合测量的三段区间的位移行程，Δx为商用干涉仪测量的三段区间的位移行程。以商用激光干涉仪的位移行程Δx为基准，计算了Δx_g关于Δx的相对误差，结果表明修正后的光栅自混合干涉仪的位移相对误差值小于 0.30%。

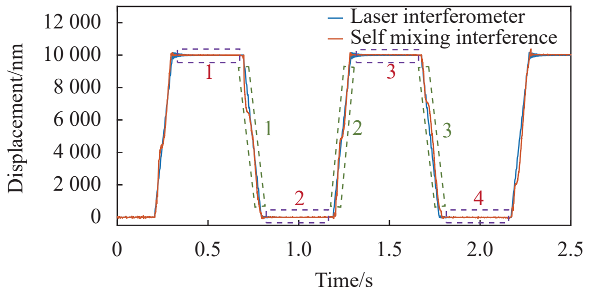

图 8 商用干涉仪与光栅自混合干涉仪重构位移比对图

Fig.8 Comparison diagram of reconstructed displacement between commercial interferometer and grating self-mixing interferometer

表 2 商用干涉仪 QuDIS 与光栅激光自混合干涉仪位移比对测量表

Tab.2 Displacement comparison measurement table between commercial interferometer QuDIS and grating laser self-mixing interferometer

Index	$\bar{x}$/nm	$\bar{x}$ of QuDIS/nm	Δx/nm	Δx of QuDIS/nm	Error
1	10 006.52	10 003.30	10 005.8628	10 000.0875	0.058%
2	0.6572	3.2125	−10 016.4298	−10 003.8375	0.126%
3	10 017.087	10 007.05	10 023.5872	9 999.4695	0.241%
4	−6.5002	7.5805	-	-	-

2 结 论

文中研究了基于平面衍射光栅反馈的激光自混合纳米位移测量方法，提出了运用反余弦方法进行相位解包裹的计算方法。在弱反馈条件下进行了实验研究，基于反余弦方法重构了实验结果，并且与商用激光干涉仪的测量结果进行了比对。实验结果表明，基于平面反射光栅的激光自混合干涉仪实现了高精度的纳米位移测量。实验系统的相位噪声引起的平均位移涨落为 5.82 nm。以商用激光干涉仪的位移测量值为基准，经过 1.1086 的系数修正后的光栅激光自混合干涉仪的位移测量误差不超过 0.241%，说明了多次位移测量依然具有较好的重复性。位移测量误差主要的来源包括闪耀全息光栅的周期不均匀性、光栅表面粗糙度以及电子学噪声。实验结果表明：基于平面衍射光栅反馈的激光自混合干涉方法可以作为一种有效的纳米位移测量方案。未来通过优化光栅自混合测量系统，比如采用由电子束直写制备的高精密光栅或者原子光刻技术制备的原子沉积光栅等结

构均匀性更好、表明粗糙度更小的光栅反馈元件，或者采用机器学习相关算法减小噪声电子束噪声对于自混合信号的影响，可以进一步提高光栅自混合干涉仪的测量准确度和精度。

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Research on laser self-mixing nano-displacement measurement based on plane reflective holographic grating

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Abstract:

Objective Nano-displacement measurement technology is an important branch in the field of precision measurement, its development and improvement are important guarantee for realizing high-precision nano-manufacturing. With the rise of laser self-mixing interference technology, the precision displacement measurement method with simple structure, low manufacturing cost and measurement accuracy up to nanometer level has been vigorously developed. Laser self-mixing interference technology has been widely used in displacement measurement, absolute distance measurement, speed measurement, and vibration measurement, etc. With the advantages of single optical path structure and the comparable measurement accuracy as double beam interference, the self-mixing interference technology has better application prospect in the industrial area. Traditional laser self-mixing interference schemes mostly take mirrors or scattering surfaces as target mirrors, which take laser wavelengths as measurement benchmarks and are easily disturbed by environmental changes. In order to increase the robustness of the measurement benchmark, this paper studies a laser self-mixing nanometer displacement measurement method based on a planar reflective holographic grating. Different from traditional laser self-mixing interference, the displacement measurement value based on grating feedback is determined by the period of the grating.

Methods For the laser self-mixing displacement measurement method based on the plane reflective grating feedback, the vibration displacement value of the holographic grating is reconstructed in this paper. The displacement measurement value of this method is based on the grating period. The system setup is shown (Fig.1). The light emitted by the laser is incident on the grating surface at the Littrow angle, so the retro-reflect one-order diffraction light carry the Doppler phase shift caused by the displacement along the grating period direction. The self-mixing interference output laser is splitted by the structure composed of a half-wave plate and a polarized beam splitter, and the self-mixing signal is collected through a photodetector. In terms of signal processing, the grating self-mixing interference signal is firstly denoised by a low-pass filter and then normalized. Combining the threshold setting method to decide the inversion point of the displacement direction and the phase unwrapping algorithm of arccosine, the displacement of the grating is reconstructed. The grating used in this experiment is a plane diffraction grating with the period of 2400 lines/mm, which equals 416.67 nm. The constructed displacement is compared with the measurement result of a commercial laser interferometer.

Results and Discussions In the grating self-mixing interference experiment, the signal under the condition of weak feedback intensity was measured, and the normalized interference signal was shown (Fig.5). After signal processing based on the arccosine method, the corresponding nano-displacement reconstruction results were obtained (Fig.7). The result represents the linear displacement of reciprocating motion as shown in the experiment setting. By calculating the variance of the linear displacement, the entire system has a displacement noise of 5.82 nm, which is expected to be optimized by performing a finer filtering on the signal. From the displacement reconstruction results, the entire measurement result has a linear deviation coefficient of 1.1086 times the actual displacement. A commercial laser interferometer and a grating self-mixing interferometer were also used to compare the displacement measurement data. After the linear correction, the measurement results show that the displacement error does not exceed 0.241% (Tab.2).

Conclusions Laser self-mixing nano-displacement measurement method based on the feedback of a planar diffraction grating is studied in this article, and a calculation method using the arccosine method for wrapping phase is proposed. Experimental research was carried out under weak feedback conditions, and the experimental results were reconstructed based on the arccosine method. Compared with the measurement results of commercial laser interferometers, it was found that the laser self-mixing interferometry method based on planar diffraction grating feedback could be used as an effective scheme for nano-displacement measurement. In the future, the measurement accuracy and precision of the grating self-mixing interferometer can be further improved by optimizing the geometric alignment, adopting a more accurate grating, and performing more effective filtering on the signal.

Key words: nano-displacement measurement; laser self-mixing; grating interferometer; holographic grating

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