中国激光

基于分光光度法的差分信号精确测量高反镜反射率

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摘要 目前，高反射率反射镜在激光陀螺和引力波探测等领域中有着广泛的应用。但对于反射率为99.9%～99.99%的样品，现有测试手段存在一定局限性。搭建了基于分光光度法的反射率测量装置，采用双光路测量方法，通过测量参考信号和基准信号、参考信号和测试信号的差分信号来计算反射率。与绝对值较大的参考信号、基准信号和测试信号等相比，信号差值本身相对较小，因此可以充分利用锁相放大器的灵敏度来提高反射率的测量精确度。所介绍的测量方法的精确度可达10^{-5}，与光腔衰荡法进行对比，测量误差在0.009%以下。所提方法用简单的装置就能达到较高的精确度，满足99.9%～99.99%反射率的精确测量需求。

关键词 测量；激光光学；高反射率；分光光度法；光学薄膜；锁相放大器

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1 引 言

高反射率反射镜的损耗极低，在基于电子跃迁的高功率红外激光系统和短波长激光系统[1]、干涉仪[2]、环形激光陀螺[3]、惯性约束聚变(ICF)[4]系统和引力波探测[5-6]等领域中有着广泛的应用，其反射率对这些系统的性能提升有着举足轻重的影响。其中，在光通信器件中，光学微腔内反射镜的反射率需要达到99.9%以上[7-8]，光学陀螺仪对反射镜的要求是反射率不低于99.99%[9-10]。高反射率反射镜应用范围的扩大及其光学性能的提高使得准确测量高反射率成为迫切的需求。

目前广泛使用的反射率测量方法是分光光度法[11-15]。分光光度法分为单光路和双光路。在单光路测量中，参比样品的化学稳定性、反射率特性等均会影响测量精度，而且参比样品的反射率应尽量接近，最好略高于待测样品的反射率。在高反镜的反射率测量过程中，很难找到这样的参比样品。目前，可以通过在分光光度计中引入V-N型、V-W型光路[16]或积分球[17-18]等附件，实现绝对反射率的测量，加入附件之后，不需要使用参比样品。除此之外，单光路测量对光源、系统稳定性的要求较高，测试速度较慢。与之相比，双光路测量方法降低了光源稳定性对测量精度的影响，测试速度相对更快，目前其不确定度已经可以达到0.05%，但与超高反射率元件的实际需求仍有一定差距。

光腔衰荡(CRD)法[19-20]是一种基于低损耗无源谐振腔的高精度光学检测技术，但相较于分光光度法，其装置结构更复杂，调节难度较高。CRD法通过对信号相位及幅值进行拟合得到衰减时间，进而求得反射率。当反射率越小、腔内损耗越大时，衰减时间就越短，导致测量困难，误差增大，所以CRD法的测量精确度随着样品反射率的降低而降低[21-22]。

本文基于分光光度法测量光学元器件反射率，并搭建了装置。通过测量参考信号与基准信号、参考信号与测试信号的差分信号来计算反射率，与传统测量方法相比，测量精确度得到提高。

2 原理及装置

传统双光路分光光度法测量反射率的基本原理如图1所示，光源发出的光被分成两束，一束经过放有样品的样品池后作为测试光，另一束光经过与样品池一样的参比池后作为参考光，光束选择调制器将两束光束分别射入光电传感器，使得光电传感器交替探测到测试光的光强I_1和参考光的光强I_0。将两束光的光强

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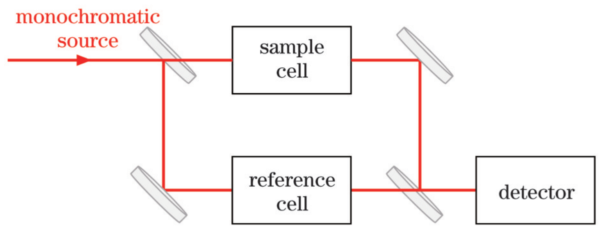

图1　双光路分光光度法的基本原理

Fig. 1　Basic principle of double optical path spectrophotometry

信号相除，即可得到样品的反射率 $R=I_1/I_0$[23]。

本文提出的测量装置基本结构如图2所示，其中光源采用半导体激光器，输出单色线偏振光，代替传统分光光度法的灯光源。连续输出的光束通过斩波器后成为脉冲信号，并入射到楔形片上，楔形片的前、后表面向不同方向反射光束，其中前表面反射光光路为参考光路，后表面反射光光路为基准光路，分别用探测器接收并转换为电信号输入到锁相放大器（LIA）中。斩波器输出同步信号到LIA中作为参考信号。空测时，利用LIA可测得参考光路的信号强度。参考光路的信号强度与基准光路的信号强度之差为

$$V=V_1-V_2, \tag{1}$$

式中：V_1为不放置样品时参考光路的信号强度；V_2为不放置样品时基准光路的信号强度；V为不放置样品时LIA测得的差分信号。

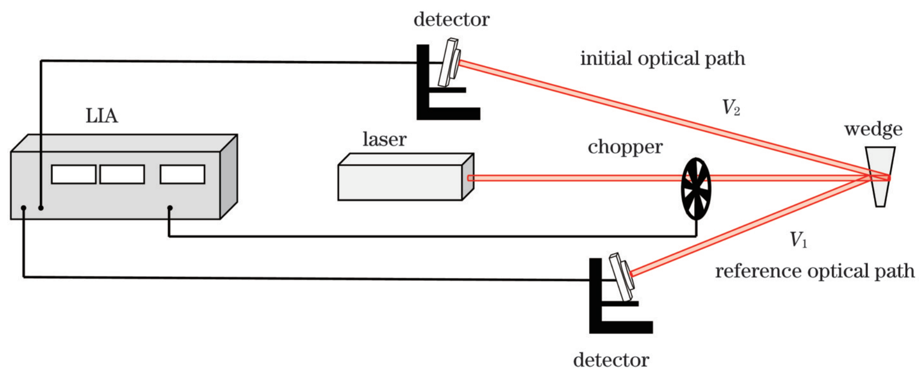

图2　基准光路示意图

Fig. 2　Schematic of initial optical path

在图3所示的位置中插入样品，将基准光路探测器移至图3中位置，此时，楔形片前表面的反射光光路为参考光路，楔形片后表面的反射光光路为测试光路。利用LIA可测得有样品时参考光路的信号强度与测试光路的信号强度之差为

$$V'=V_1'-V_2', \tag{2}$$

式中：V_1'为放置样品时参考光路的信号强度；V_2'为放置样品时测试光路的信号强度；V'为放置样品时LIA测得的差分信号。

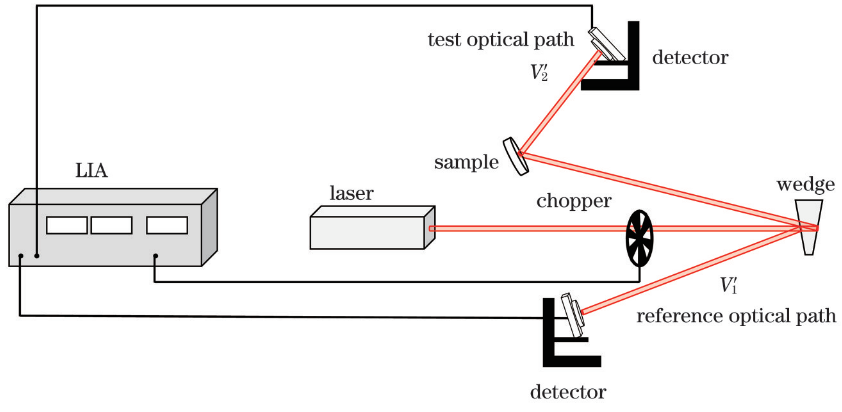

图3　测量样品反射率的光路示意图

Fig. 3　Schematic of optical path for measuring sample reflectivity

相比于经过斩波器后直接在前表面发生反射的光，辐照在基准光路探测器上的光束在楔形片后表面反射前、后各经过了一次衰减，基准光路探测器接收到的光束强度弱于入射到参考光路探测器的光束，因此信号V为正值。在光路中插入样品后，由于透射、吸收和散射等引起的损失，入射至测试光路探测器的光强小于空测时基准光路中入射至该探测器的光强，故$V_2'<V_2$，信号V'也为正值。

由于参考光信号值不变（$V_1=V_1'$），可以计算样品的反射率R：

$$R=\frac{V_2'}{V_2}=\frac{V_1-V'}{V_1-V}。\tag{3}$$

本方法通过测量参考信号与基准信号、参考信号与测试信号的差值来计算反射率，而非直接测量参考信号值、基准信号值和测试信号值。由于相较于信号值本身，信号值之差非常小，所以可采用LIA的小量程进行测量，极大提高了测量精度。

3　测量结果与分析

3.1　装置校准

对于高反射元件，元件前、后的光束功率变化极小，即对应的 V_2 及 V_2' 非常相近，这样细微差别的测量需要LIA有极高的分辨率与精确度。装置中用到的锁相放大器的幅值测量精确度为量程的1%，因此实验中尽量采用更小的量程以提高测量精度。对于本装置而言，需要参考光路与基准光路信号尽量接近，从而使两路信号差值 V 及 V' 尽可能小。

两路光束分别是由楔形片的前、后表面反射形成的，由于经过前表面的两次反射衰减，后表面反射的光束强度比前表面反射光束强度稍低，这在一定程度上限制了装置测量极限，因此本装置在光电探头输出端配备了匹配电阻以调节输出电压，在信号幅值为~60 mV时可以将两路信号差控制在200 μV左右，对应的测量精确度达到0.1 μV。

所选取的光电探头体积小，稳定性好，对1064 nm波段的响应率比较高，采用干电池供电以保证输出稳定。但探测器的通光窗口未镀制增透膜，窗口玻璃前、后表面的反射光可能形成干涉，导致探测器测量结果对波长漂移、光束指向以及环境的扰动极为敏感，从而测量稳定性受影响，因此在通光窗口前附加了一块毛玻璃以形成散射光，避免干涉的形成。

本装置工作的前提是探测器的转换效率固定，在输入光束功率相同的条件下，转换出的电压信号也应相同，但实际上有一定难度。探测器口径大于光斑直径，不同位置的感光器件响应存在一定差别，从而带来误差。为了避免该问题，设计时将探测器固定在 X-Z 二维移动平台上，并调节位置令光束辐照在转换效率最高的位置处，以此固定转换率。

此外，光源输出功率波动也会影响测量结果。主要原因在于探测器转换信号强度与功率成正比，可以看作是光束功率乘上一个系数因子，但由式(3)可以看到，计算反射率时需要用到两者之差，因此输入功率不同时计算结果也不同。为了消除光源波动的影响，实际测量过程中对每个样品都进行参考光路、测试光路信号的测量，并尽量缩短时间，控制在5 min甚至3 min之内，从而降低对光源输出稳定性的要求。

3.2　测量结果

利用本装置对两片波长为1064 nm、使用角度为45°的高反镜样品进行测量，镜片直径为50 mm，厚度为5 mm。样品1#是采用磁控溅射法制备的，以 Ta_2O_5、HfO_2 作为高折射率材料，以 SiO_2 作为低折射率材料，基底为石英的单面反射镜。样品2#是采用双离子束溅射法制备的，以 Ta_2O_5 和 SiO_2 分别作为高折射率材料和低折射率材料，基底为石英的单面反射镜。

光源选用半导体激光器，连续输出波长在1064 nm附近的光束，功率为241.5 mW。光斑模式为 TEM_{00}，光束质量因子(M^2)<1.2，直径为1.8 mm(图4)。4 h内的均方根(RMS)激光输出功率稳定性<0.1%。实验中根据样品设计及测试需求，设置入射角为45°，测量样品1#时采用S偏振光，测量样品2#时采用P偏振光。

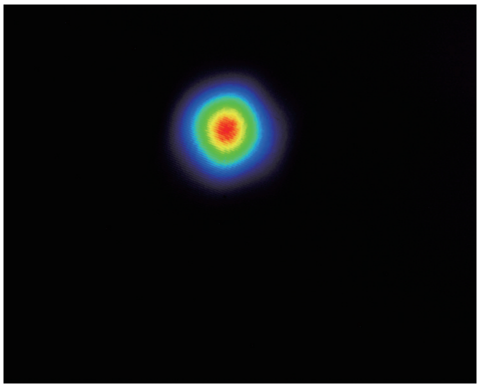

图4　激光器输出的光斑

Fig. 4　Laser output spot

为了验证装置的精确度，进行了多次测量，其反射率测量数值 $\bar{R}$ 的计算公式为

$$\bar{R}=\frac{\bar{V}_1-\bar{V}'}{\bar{V}_1-\bar{V}},\tag{4}$$

式中：$\bar{V}_1$、$\bar{V}'$、$\bar{V}$ 分别为多次重复测量过程中得到的 V_1、V'、V 的平均值。

反射率 $\bar{R}$ 的总不确定度的几项来源 $u(x)$ 为

$$u(x)=\sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i-\bar{x})^2},\quad x=V_1,\ V',\ V,\tag{5}$$

式中：$u(x)$ 包括参考信号 V_1、有样品时参考光路信号强度与测试光路信号强度之差 V'、空测时参考光路信号强度与基准光路信号强度之差 V 三项；x_i 为第 i 次测量结果；n 为重复性测量次数。

反射率的总不确定度 $u(R)$ 为

$$u(R)=\sqrt{\left[\frac{\partial R}{\partial V_1}u(V_1)\right]^2+\left[\frac{\partial R}{\partial V'}u(V')\right]^2+\left[\frac{\partial R}{\partial V}u(V)\right]^2},\tag{6}$$

式中：$u(R)$ 为综合 V_1、V'、V 这三项的总不确定度。

分别用本装置与CRD法测量两片高反镜样品，测量结果如表1所示，CRD法选用的入射角、激光波长和偏振态等测量参数与本装置的测量参数一致，两个样品的反射率测量结果不确定度均在0.01%以下。由

于间接测量运算结果的有效数字位数由绝对误差决定，间接测量值应与绝对误差保持在同一量级。本文通过不确定度传递公式计算误差，误差保留一位有效数字时，其为10^{-5}量级，故反射率计算结果也为同样量级，满足高反镜的反射率测量需求。且本测量方法不需要利用参比样品标定，装置简单，操作简便。CRD法测量结果由成都技致光电科技有限公司测量给出，CRD法的精确度高于本测试装置一个数量级，本装置的测试结果与CRD法测量结果的相对误差在0.009%以下。

表1 高反射率薄膜样品的反射率测量结果

Table 1 Measured reflectivity values of high reflectivity film samples

Sample	Measured reflectivity /%	
	Spectrophotometry	CRD
1#	99.954±0.009	99.9537±0.00033
2#	99.986±0.009	99.9949±0.00022

3.3 误差分析

装置给出的测量结果与CRD法稍有差异，原因可能有以下三点。首先本测量装置中使用的激光器波长并非严格的1064 nm，同时含有部分1078.5 nm波长，而CRD测试波长为单色1064 nm，因此两种测量手段的结果出现偏差，这可以通过选用严格单色光源来消除。此外，测试装置中的探测光路与基准光路之间可能存在光程差，而激光器出射光束存在一定发散角，这样辐照到探测器的光束尺寸有所差别，从而导致测量V及V'时出现光电转换效率差异，影响输出信号大小。最后，光程差的存在还导致基准信号与参考信号、探测信号与参考信号之间相位差，由于LIA的工作原理，相位差的引入将导致信号测量值的变化。

相位对LIA的影响可以从以下推导得出。LIA的探测信号V_t与参考信号V_r可以表示为

$$V_t = A\sin\left(2\pi\cdot f_t\cdot t\right), \tag{7}$$

$$V_r = \sin\left(2\pi\cdot f_r\cdot t+\varphi_0\right), \tag{8}$$

式中：A为测试信号振幅；f_t和f_r分别为探测信号和参考信号的频率；t为时间；φ_0为探测信号与参考信号的相位差。LIA在测量过程中，将参考信号与探测信号相乘，得到混有两种频率(原信号频率和及原信号频率差)的信号V_{signal}：

$$V_{signal} = V_t\times V_r = \frac{A}{2}\times\left\{\cos\left[2\pi\times\left(f_t-f_r\right)\times t-\varphi_0\right]-\cos\left[2\pi\times\left(f_t+f_r\right)\times t+\varphi_0\right]\right\}。 \tag{9}$$

LIA会滤除高频信号，即$\cos\left[2\pi\times\left(f_t+f_r\right)\times t+\varphi_0\right]$项，得到低频信号，即原信号频率差的幅值与相位。在本装置中，参考信号(斩波器信号)与探测信号(探测器信号)同频，有$f_t=f_r$，输出的频率差信号V_{output}为直流信号：

$$V_{output} = \frac{A}{2}\times\cos\varphi_0。 \tag{10}$$

由式(10)可以看出，任何微小的相位浮动都会直接表现为LIA信号强度的变化，从而引入测量误差。所以为了得到最优的结果，保证参考光路与测试光路的光程相同并尽量减小相位差是非常重要的。

由以上分析可以看出，测量误差多是光源及装置调试引入的，因此有理由相信选用更标准的激光器作为光源并精细调试，本方法可以进行更高精度的反射率测量。

4 结 论

提出的分光光度法通过测量差分信号来计算反射率，提高了测量精度。装置校准中通过快速固定机构、缩短测量时间、降低光源波动影响等手段保证了测量结果的准确性，所提方法非常适用于高反射率的测量。与传统测量方法相比，所提测量方法以相对简单的装置实现了高反射率的测量，特别是在99.9%反射率附近，解决了现有技术的测量问题，填补了商业化分光光度计与CRD技术之间的空白。

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Accurate Measurement of Reflectivity of High Reflectivity Mirror by Differential Signal Based on Spectrophotometry

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Abstract

Objective Currently, high-reflectivity optical elements are widely used in optical fields, such as ring laser gyroscopes, inertial confinement fusion systems, and gravitational wave detection. Their reflectivity values have a decisive influence on the performance improvement of these systems; therefore, accurate measurement of their reflectivity values is necessary to optimize the system performance. At present, there are many measurement methods, among which spectrophotometry and cavity ring-down (CRD) technology are the most widely used. However, these two methods have certain shortcomings. Spectrophotometry is associated with low accuracy, and its measurement limit is usually lower than 99.9%; especially when measuring high reflectivity (>99%), its accuracy is reduced. Devices using CRD technology for high reflectivity measurement are relatively complex and expensive, and the measurement conditions, such as adjusting the incident angle and polarization state, are inflexible. Moreover, according to the measurement principle, the lower the reflectivity of the sample to be measured, the lower is the measurement accuracy. Therefore, for samples with the reflectivity of 99.9%–99.99%, existing testing methods have some limitations. Based on the described situation, it is necessary to study a high-precision reflectivity measuring device that can measure the reflectivity of 99.9%–99.99% accurately. It is necessary to develop a reflectivity measuring device which has the advantages of simple device, convenient adjustment and good measurement stability.

Methods Based on traditional spectrophotometry, we study a more accurate reflectivity measurement method. The main improvement in this method is measuring the difference signal instead of the reflected light and incident light signal. In this study, a reflectance measuring device based on spectrophotometry is developed, which adopts a double-path measurement. First, we measure the signal difference between the reference optical path and the initial optical path without samples, and the reference optical path signal (Fig. 2). We then measure the signal difference between the reference optical path and the test optical path after placing the sample (Fig. 3). The reflectivity of the sample is calculated according to the measured reference and differential signals. The reflectivity is calculated by measuring the difference between the reference signal and the initial signal and the difference between the

reference signal and the test signal. Compared with the reference signal, initial signal, and test signal with larger absolute values, the signal difference itself is relatively small; therefore, the sensitivity of the lock-in amplifier can be fully utilized to improve the reflectivity measurement accuracy. In addition, we use a quick fixing mechanism to shorten the measurement time and reduce the influence of unstable factors such as the light source and environment on the experimental results. In the experiment, there are some differences in the responses of the detectors' photosensitive devices at different positions; therefore, mobile platforms are installed at the three positions where the two detectors are placed. Before the formal measurement, the position of the detector is adjusted to ensure that the beam irradiates the position where the conversion efficiency is the highest on the receiving surface of the detector .

Results and Discussions We use this device and the CRD method to test the highly reflective mirror samples. The wavelength in the two methods is 1064 nm, and the incident angle is 45°. The high-reflection wavelength of the two high-reflection mirror samples is 1064 nm, the use angle is 45°, the lens diameter is 50 mm, and the thickness is 5 mm. The two samples are measured using S-polarized light and P-polarized light, respectively, and the highest reflectivity is 99.986% (Table 1). In this study, the error is calculated using an uncertainty transfer formula. When only one significant digit is retained, the error is of the order of 10^{-5}, so the reflectivity calculation result is also of the same order, which meets the reflectivity measurement requirements of a high reflector. The accuracy of the measurement method introduced in this study reaches 0.01%. Compared with the CRD method, the measurement error is less than 0.009%, which shows that this method can achieve a higher measurement accuracy with a simpler device. The advantages of this device are as follows: 1) By using a lock-in amplifier to measure the signal with high precision and a small range and shortening the measurement time, higher accuracy can be achieved; 2) The sample fixture is installed on the rotating platform, and the adjustable position range of the detector of the test optical path is large, so the adjustable incident angle range of the device is also large; 3) The device is simple and easy to operate.

Conclusions In this study, traditional spectrophotometry is improved, the measurement accuracy is increased by measuring differential signals, and the high-precision range of the lock-in amplifier is fully utilized. In addition, in the calibration of the device, the measurement time is shortened by means of a quick fixing mechanism, and the influence of light source fluctuation is reduced, which ensures the accuracy of the measurement results. The measurement accuracy can reach 0.01% stably, which meets the measurement requirements of the existing high-reflector elements, compensates for the shortcomings of the traditional measuring methods, greatly increases the application range of spectrophotometry, and fills the measuring gap between commercial spectrophotometry and CRD technology in the reflectivity range of 99.9%–99.99%.

Key words measurements; laser optics; high reflectivity; spectrophotometry; optical film; lock-in amplifier