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A precise maesurement of reflectivity of the laser cavity mirrors. A method to balance the intensities of two light beams with single detector*

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A new measuring system is suggested to measure precisely the high reflectivity of the laser cavity mirrors. In this system a laser light is divided by a splitter into two beams, one of which is used as the reference. That is why the high stability of light source is unnecessary. To compare the intensities of two beams and to indicate the intensity balance only a single detector and its electrical circuit are required. Thus the strict linearity of the detector is unnecessary.

The tests of this experimental device show that a relative measuring accuracy (repetition) of 0.02 % can be exeeded at the wavelength of 0.63 and 1.15 μm. The absolute measuring accuracy of the same order may be approved.

This way of measurement can be easily realized. The reflectivity distribution of all over the mirror can be obtained point by point. The automatic measurement can be easily realized.

1. Introduction

In many fields of laser research one of the major problems is a high optical quality of thin film dielectric coatings for cavity mirrors. To improve the coating technology the measurement of reflectivity should be highly precise of order of 10^{-4}. In several works published so far [1–8] this problem has been solved in different ways by satisfying the desired requirements for different wavelength range and with different accuracy. The measuring system suggested in this research work has a number of distinguishing features. It does not require the highly stabilized light nor strict linearity of photoelectric detector, but assures a relatively high precision of measurement by using this really not complicated device. It is also possible to measure the curved mirror with the same accuracy as the flat one, and the reflectivity can be measured for different spots on the mirror surface, with the required incident angle.

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2. Measuring system and experimental device

The optical arrangement of this experimental measuring system is shown in Fig. 1. As a light source S a He-Ne laser generating a linear polarized TEM_{00} mode is used. Its output beam is split into two beams by an optical splitter M_0. Both beams pass alternatively through a rotating modulator RM. Light source and detector are mounted on the modulator to generate the control signal with a fixed phase shift. The beam I_1, used as a reference, reflected by a mirror M_2, passes through the lens L_1, the quartz window W (which is

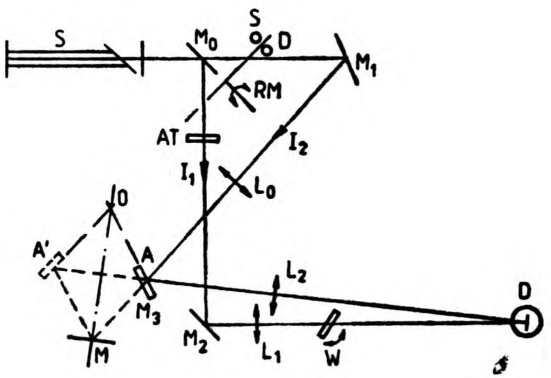

Fig. 1

rotatable optical compensator) to be finally projected onto the photodetector D. The other beam I_2, called measuring beam, is first directly projected on the same detector D through L_0, M_3 and L_2. Then, the mirror M_3 is rotated around the axis 0 from the position $0A$ to $0A'$, so that the measured mirror M is inserted in the measuring beam path I_2. The rotation angle of the mirror M_3, the position of the measured mirror M and the direction of its normal are determined by the incident angle required. The normal of the spot measured on the mirror M must pass also through the axis 0 and be perpendicular to the beam I_2.

A high quality quartz window W is placed in the centre of rotatable disk, its rotating axis is perpendicular to the beam I_1 and intersects it. The accuracy of readout of the angle position of W must be better than 1 minute. The transmittance T of the window is a known function of its angle position.

AT is an adjustable optical attenuator, by which the beam I_1 intensity may be adjusted to equal the beam I_2, when the measured mirror is not inserted and the window is set on the optimum position.

Lens L_0 is used to focus the Gaussian beam, if the laser beam waist is located on the measured mirror surface. Thus, a curved mirror with larger radius of curvature may also be measured with the same accuracy. The lens L_2 used to transform the Gaussian beams before and after the measured mirror is inserted to make the light spot on the detector surface of the same size. The beam I_1 is projected onto the detector with the same size through the lens L_1.

The electronic circuit is shown schematically in Fig. 2. Its distinguishing feature is the single canal with single detector. Its main function is to state whether the intensities of two beams projected alternately onto the detector are equalized. Hence the detector need not be strictly linear. As far as selection of an available photodectector is concerned, the following feature are requested: a better sensitivity, a higher signal-to-noise ratio, a sufficiently sensitive area, the latter being less inhomogeneous over photodetector surface.

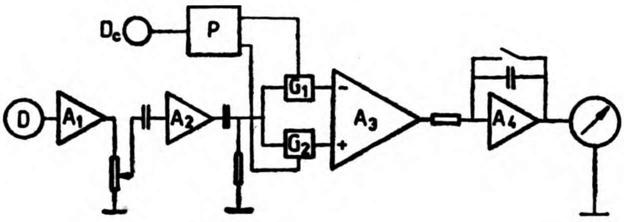

Fig. 2

A_1 is a preamplifier located in the detector case. A_2 works as an alternative signal amplifier. If the intensities of beams projected alternatively are not equal, then there appears a signal in form of a rectangular wave to be put out by A_2. The signal will then be controlled by two electronic gates, and the signals of two half periods will be sent to two input terminals of a differential amplifier A_3. The output signals provide a direct voltage proportional to the sum of input signals.

In order to avoid the influence of unstability during the wave transition on the measuring accuracy, two electronic gates G_1 and G_2 are used to cut off a part of input signal by the synchroneous pulses coming from the gate-controlled pulse generator. The signals of two half periods become then strictly rectangular and equal in time.

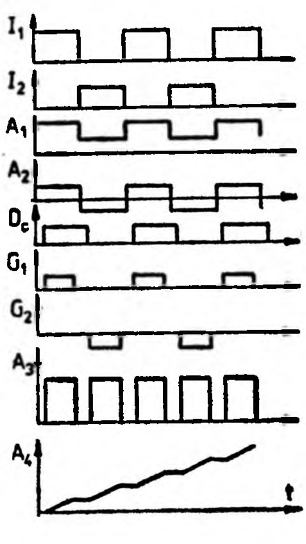

Fig. 3

The integral amplifier A_4 processes the direct input voltage within any selected integration time T (sec), so that all the noise components of the frequencies greater than $1/T$ Hz are filtered out. Hence, by extending the integraton time not only a higher sensitivity is obtained, but also more noise components are filtered.

The waveform diagram of different point in the circuit presented in Fig. 3 shows that there will be an integral output if there exists even a slight difference between the I_1 and I_2 intensities which is indicated by the sign of the integral output.

3. The theory of measurement and its procedure

The optical system must be carefully adjusted and aligned before the measurement is started. High stability of the beam axis must be strictly ensured. First, the mirror M_3 is to be put in its original position $0A$ and then the window W rotated untill the output of integrator becomes null. Then the angle position must be read out and its corresponding transmittance T_1 calculated. This operation is called the first measuring operation.

Assume that the response of the photodetector has unlinear characteristics, i.e., the sensitivity B varies with the input light intensity.

During the first measuring operation let the laser output be I. The splitter M_0 and attenuator AT have a total dividing ratio $m_1 : m_2$. The responses S_1 and S_2 of I_1 and I_2 on the photodetector D may be expressed as follows:

$$S_1 = m_1 R_2 t_1 B I T_1, \tag{1}$$

$$S_2 = m_2 R_1 t_0 R_3 t_2 B I \tag{2}$$

where B is the sensitivity, t_0, t_1 and t_3 are the transmittance of lenses L_0, L_1 and L_3, respectively. If intensity is in equilibrium $S_1 = S_2$. From (1) and (2) we have

$$T_1 = m_2 R_1 t_0 R_3 t_2 / m_1 R_2 t_1. \tag{3}$$

Then the mirror M_3 is to be rotated to its new position $0A'$ and the window W rotated again to a new angle position as the integrator output becomes null again. This is the second measuring operation. We assume that the laser output becomes I'. The photodetector response S_1' and S_2' can be written as

$$S_1' = m_1 R_2 t_1 T_2 B I', \tag{4}$$

$$S_2' = m_2 R_1 t_0 R R_3 t_2 B' I'. \tag{5}$$

Similarly, we have

$$T_2/R = m_2 R_1 t_0 R_3 t_2 / m_1 R_2 t_1. \tag{6}$$

By comparing (3) and (6), we can get the measured reflectivity R as

$$R = T_2/T_1. \tag{7}$$

The Equation (7) is termed the measuring formula. Its simplest form shows that the measured reflectivity is related only to the transmittance of the window W and this fact explains why the high stability of laser intensity and detector linearity are not required.

4. Experimental results

Several groups of experimental results are listed in the following Table:

Sample No.	1	2	3	4	5
Wavelength (μ)	0.63	0.63	1.15	1.15	1.15
Polarization	S	S	P	P	P
Incidence angle (deg)	9	9	30	30	30
Radius of curvature (m)	∞	∞	∞	2	∞
Measured reflectivity (%)	99.719	97.363	98.929	99.380	98.251
	99.711	97.359	98.921	99.377	98.260
	99.717	97.357	98.941	99.389	98.250
R (%)	99.716	97.360	98.930	99.382	98.254
ΔR_{max}(%)	0.008	0.006	0.020	0.012	0.010
Used detector	Si cell Ø 10		Ge triod Ø 8		

5. Analysis of accuracy

The measuring formula (7) was determined under the assumption that both beams I_1 and I_2 are transformed with the same sensitivity of the detector and that the loss of each optical component in the system remains unchanged during two measuring operations. Any change in their values will introduce a measuring error. The random drift of these parameters causes a deviation of measured reflectivity, we call it repetition. It may be determined experimentally.

If these parameters are changed with the measuring process, the result will differ from the correct value. A part of their difference, called systematic one may be corrected by calculation. The sum of the remaining parts and the repetition are called an absolute accuracy.

In the following we shall analyse the main sources of error.

1. Error from the inhomogeneous sensitivity over the detector surface:

A typical data attributed to the detector used are 0.01%/0.1 mm for the light spot size about ⌀ 2 mm. The absorptance of both beams on the detector surface is insensitive to the variation of incident angle, because they both are symmetrically and near-normally projected onto the detector surface. Any uncoincidence or difference in size of the two beams on the detector surface will cause a small difference between B_1 and B_2 sensitivities, i.e., $B_2 = (1+\varepsilon)B_1$.

If we rewrite the Eqs.(1)–(7) using this relation, we may find the same measuring formula. Hence, this error is negligible.

2. Error from the rotation of the window W:

Since the rotating window has its own thickness d (2–3 mm), then different angular positions of two measuring operations cause the spot displacement of 0.01–0.06 mm and an incident angle on the detector surface is changed less than by 10′. The error from the inhomogeneous sensitivity is about 5×10^{-5}.

The absorptance k of the window is about 2×10^{-4} mm and the path difference in the window between two measuring operations may reach 0.38 mm, which may cause an error of about 7.5×10^{-5}. This error is systematical and can be corrected.

3. Error occurring when a curved mirror is measured:

Let the mirror have a radius of curvature q. Since the Gaussian beam waist was focussed by the lens L_0 on the surface of measured mirror M, the waist will be imaged again. The image distance l' and the waist size W_0' may be calculated from the following equations [9]:

$$l' = q/2\left[1-\frac{1}{1+\left(\frac{2\pi W_0^2}{q\lambda}\right)^2}\right], \tag{8}$$

$$W_0' = W_0\Big/\sqrt{1+\left(\frac{2\pi W_0^2}{q\lambda}\right)^2}. \tag{9}$$

Assuming $q = 1000$ mm, $W_0 = 0.095$ mm, $\lambda = 0.00115$ mm, we shall have $l' = 1.2$ mm and $W_0' = 0.99878\, W_0$. It can be seen that the beam waist has a very small axial displacement and a size change of 1.2×10^{-3}. They are completely negligible.

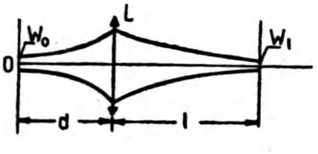

Fig. 4

4. Error from the misalignment of the lens L_2:

The propagating law of a Gaussian beam through a thin lens with focus length f is well known as [9] (see Fig. 4)

$$W^2(l) = (\lambda/\pi W_0)^2\{[(f-1)d+fl]^2+(f-l)^2(\pi W_0^2/\lambda)^2\}. \tag{10}$$

When $l = f$, Eq. (10) becomes

$$W(f) = \lambda f/\pi W_0. \tag{11}$$

From Eq. (11) it may be seen that the spot size on the focal plane of a lens is not related to the distance of beam waist in front of the lens. From (10) we can obtain the variation of spot size on the detector surface due to the misalignment of lens L_2

$$\Delta W_f \doteq \frac{dW(l)}{dl}\bigg|_{f=l} \Delta l = \frac{\lambda(f-l)}{\pi W_0 f}\Delta l. \tag{12}$$

The displacement of the beam waist in two measuring operations is $\Delta d = d_2 - d_1$, thus we have

$$\Delta W = \Delta W_{1f} - \Delta W_{2f} = \frac{\lambda}{\pi W_0 f}\Delta d \Delta l. \tag{13}$$

From Eqs. (11) and (13) we can get the relative variations of spot size as

$$\Delta W/W = \frac{1}{f^2}\Delta d \Delta l. \tag{14}$$

Let $f = 400$ mm, $\Delta d = 200$ mm, a possible misalignment $\Delta l = 10$ mm, then $\Delta W/W = 0.0125$. From the discussion in Section 1 the error caused by this spot size variation will be less than 2×10^{-5}.

5. Error from the spot size change on the lens L_2:

Since there is a displacement of beam waist Δd in two measuring operations, there also will be a spot size variation on the surface of lens L_2. The divergence of a Gaussian beam is $\theta = 2\lambda/\pi W_0$, and $\Delta W = \theta\Delta d$. Let $\Delta d = 200$ mm, $d_1 = 300$ mm, $W_0 = 0.095$ mm, $\lambda = 0.00115$ mm. We have $\Delta W = 1.56$ mm, $W_1 = 2.34$mm, and $\Delta W/W_1 = 0.67$. A relatively large variation of spot size on the lens L_2 may cause an unnegligible error in case of some inhomogeneous loss in L_2. Therefore to minimize this error to a value less than 5×10^{-5} a high optical quality lens L_2 is required.

6. Conclusions

The conclusions resulting from the carried-out analysis are summarized below:

1. The experimental results show that the relative accuracy of measurement is better than 0.02% (repetition). And the careful analysis has confirmed that the absolute accuracy has the same value.

2. The method discussed may be used to measure curved mirror with large radius of curvature.

3. It may be used at any wavelength.

4. This device is relatively simple and easy in realizing automatic measurements.

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