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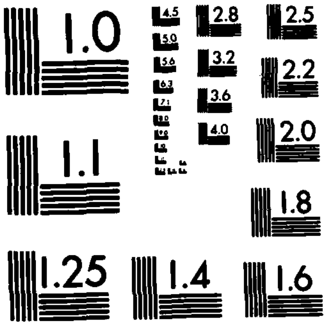

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by

Chian Shinan and Wan Jinhua

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THE OPTICAL SYSTEM DESIGN OF A VERSATILE LASER INTERFEROMETER

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[Abstract] Exploiting the advantages of the laser, we have developed an easily operated, highly precise and versatile multi-purpose polarized laser interferometer. A quarter wave-plate and polarizing beam-split prism was used so that the contrast of the interference fringes can be adjusted and the adverse effects of stray light reflected from surfaces of the interferometer eliminated. The design of the instrument and some experimental results are given here. The method which uses the emmitted light plane as the condition to fix the angle of rotation for the polarization analysing device is analysed, and the method of realizing uniform inclination interference measurement with interchangeable objectives, the apparatus of quick fringe aquisition, and the double rhomboid prism alignment system designed for operating ease are described.

I.

FOREWORD

As laser implements have the special properties of great coherence, high intensity and good directional characteristics, especially the first two, the use of laser in the area of interference has many possibilities. The JDG-1 multi-purpose laser interferometer is a small, versatile, easily operated optical measuring device. It is quite precise and can be used to measure plane, parallel, spherical and non-spherical surface errors in optical components, the evenness of the optical medium, errors in the optical system wavefront, radii for the spherical bending ratio, prism angle errors, and center inclination errors in lenses. Thus it is a very useful instrument in optics and laser laboratories and optical factories and has extensive applications in other areas as well (for example, in measuring the distribution of eletricity given off in laser chambers, or measuring the movement of gases, etc.).

Using the 1/4 wave-plate and polarizing spectroscopic prism system [1] [2] proposed by J.H. Bruning and D.R. Herriott, we reached the following conclusion after making advances in regulating contrast and analysing light intensity: there are many merits to using the outer surface through which light is thrown of the measured surface to fix the polarization analysing machine angle of rotation.

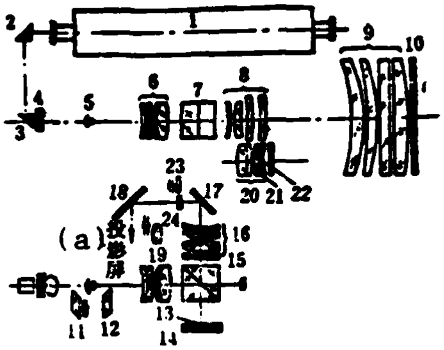
While designing the instrument we especially kept in mind that the structure of the principles should be rational, that it should have many uses, produce clear fringes, be able to use different components and be convenient to operate. The precision of the instrument is 0.06μm.

II. OPTICAL SYSTEM

The interferometer belongs to the Taiman-Green class with an optical system as in Fig.1. The beam of light emmitted from the Helium-Neon chamber passes through angular prisms 2 and 3 rotating 180°, enters the polarizer 4, passes through the condensing lens 5, objective 6, and becomes ϕ30 caliber parallel light. The parallel light passes through the polarizing spectroscopic lens 7 and is divided into two perpendicular beams of linearly polarized light.

The first beam of light reflects through a 90° rotation at the spectroscopic membrane and is a polarized beam with wave-motion direction perpendicular to the face of the paper (see lower portion of Fig.1). It passes through the 1/4 wave plate 13 to the reference lens 14 where it is reflected back on its original path again passing through the 1/4 wave-plate and polarizing spectroscopic prism to reach the polarization analysing device 15. The second beam penetrates the polarizing spectroscopic membrane and is a polarized beam with wave-motion direction parallel to the surface of the paper. It passes through a different 1/4 wave-plate and is reflected back along its original path from the measyred component to again pass through this 1/4 wave-plate and finally is reflected to the polarization analysing device 15 at the polarizing spectroscopic membrane. After passing through the polarization analysing device the two beams produce interference; from convergent lens 16 they are reflected by prisms 17 and 18 onto a ϕ110 caliber projection screen. By rotating the polarizer 4 the interference fringe contrast on the screen can be adjusted.

For the second beam of light two different calibers,ϕ30 and ϕ100 can be used as various purposes may require. The conversion from ϕ30 to ϕ100 is realized with an expanding aperture lens (8,9). When measuring plane surfaces, spherical surfaces and optical systems there are many different degrees of precision parallel surface lenses with different indices of reflection or different types of interchangeable objective appendices to supply a choice. When making measurements with a $\phi 30$ aperture, using the Michelson interference mode, a $\lambda/10$ degree of measurement precision is arrived at. In such a case, when carrying out measurements on components of differing reflection indices, the lens group can be left unchanged and the interference fringe contrast can still be adjusted. When any $\phi 100$ interchangeable lens group is used a $\lambda/10$ degree of measurement precision can still be guaranteed with the last lens in the grouping functioning as a reference lens if, using the same path, the Fisher interference mode is selected. The measurement precision for all plane surfaces is $\lambda/20$.



Key: (a) Projection screen.

Fig.1

III. POLARIZING SPECTROSCOPE AND 1/4 WAVE-PLATE SYSTEM

1. Principles in Brief

The function of the polarizing spectroscope shown in Fig.2 is to take all polarized light with wave-motion direction parallel to the z axis (perpendicular to the surface of the paper) and reflect it to the reference arm and to take all polarized light with wave-motion direction parallel to the x axis and send it through to the measurement arm. If the entering light is linearly polarized with a wave-motion direction which describes an angle α with the z axis, then we can separate it into two rays of light with wave-motion directions parallel to the x and z axes respectively according to Malus' Law with strengths of:

$$I_{\text{measured}} = I_0 \sin^2\alpha \qquad (1)$$

$$I_{\text{reference}} = I_0 \cos^2\alpha \qquad (2)$$

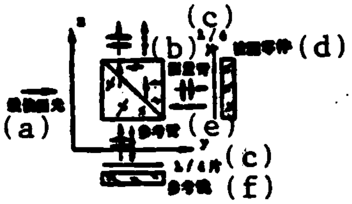


Fig. 2. (a) Linearly polarized light; (b) Measuring arm; (c) λ/4 plate; (d) Measured component; (e) Reference arm; (f) Reference lens.

If the ray is directly reflected at the reference lens, because the wave-motion direction does not change, it can only be reflected back from the spectroscope along its original path and cannot reach the projection screen. For this reason we must add a 1/4 wave plate prior to the reference lens and change the light axis and polarized direction through a 45° angle. The beam passes through a 1/4 wave-plate twice, changing the wave-motion direction of the polarized light a total of 90°; the beam then passes complete through the spectroscopic membrane to arrive at the projection screen. In the same way, we still need to add a 1/4-wave plate in the measuring arm before the measured component. By choosing the polarizing spectroscopic lens and 1/4 wave-plate system we gain the advantage described below.

2. Merits of the System

(1) Intensity of the interference fringe is heightened:

For ease of use and observation we selected a ø110 projection screen which requires that there be sufficient light intensity. In order to keep the size of the instrument from becoming too large, we chose a 250 mm laser tube. For the projection, however, we felt the light intensity might not be sufficient, and thus whether or not full enough use is made of the light becomes an important question. If a spectroscopic lens is chosen with, say, penetration and reflection each at 50%, and the ray passes through twice, then at least 75% of the light is lost. From the above description we know that the 1/4 wave-plate and polarizing spectroscopic lens system passes and reflects all the light so, theoretically, there is no loss and the light is fully exploited.

(2) The interference fringe is easily regulated and the fringe contrast is heightened:

At present, for most interference optics testing equipment, reference lenses of different reflection indices (both spherical and plane) need to be changed when components of differing reflection indices are measured making the equipment both difficult to operate and quite expensive. This instrument uses the polarizer 4 to rotate the light axis so the wave-motion direction can be changed. In this way, with any component of arbitrary reflection index, the intensity of the light beams in the reference and measurement arms after the polarization analysing machine can be regulated to achieve the best contrast and no change of either objectives or reference lenses need be made. The operation should be performed in this manner when the ⌀ 30 aperture is used for measurement.

(3) Eliminates stray light to give a clear interference fringe:

Due to the good coherence qualities of the laser, the stray light reflected from the surfaces of the components is formed into a srtay light fringe which disrupts the measured fringe, sometimes seriously enough to make distinguishing the real and spurious fringes difficult. In this system we need omly place the 1/4 wave-plate in front of the measured surface; then all the stray light reflected prior to the 1/4 wave-plate cannot reach the projection screen as its direction of polarization cannot rotate the 90°. Thus the fringe is clear and the measurement precision is heightened.

direction of polarization cannot rotate 90°. Thus the fringe is clear and the measurement precision is heightened.

(4) Design process and adjusting convenience:

Because the stray light fringe can be eliminated, we can use an aplanative lens for the interchangeable objective and greatly simplify the complicated changeable lens process. When we were designing the instrument we wanted to make the components interchangeable, so objective 6, converging lens 16, and ϕ 30 caliber are all the same. If the aplanative lens 21 is removed from objective 20 it becomes another interchangeable objective; if aplanative lens 22 is also removed then it becomes a third type of interchangeable objective. In most interference systems this kind of aplanative lens design must be completely abandoned. Experiment prooves that since the concentric surface of the aplanative lens is not plated with a transparent membrane or surface, it will not give rise to a stray light fringe.

3. The setting of the Polarization Analysing Device

As previously described, thw wave-motion directions of the two polarized beams before the polarization analysing device are perpendicular to each other, and perpendicularly polarized light cannot produce an interference fringe. For this reason the polarization analysing device for these two non-overlapping polarized directions is introduced into the main section of the light path, and the portions of the polarized light on the main section of the polarization analysing device form an interference fringe.

Set the angle between the main section polarization analysing device position and the z axis equal to β ; then, for any angle β, a corresponding angle α can be found for the polarizer. Make the two beams passing through the polarization analysing device of equal intensity; then

$$I_{\text{reference}}\sin^2\beta = RI_{\text{measured}}\cos^2\beta = I \tag{3}$$

R is the reflection index of the measured face; if is the fluctuation reflection coefficient then $\gamma^2=R$. The reference lens is a completely reflecting membrane so set its reflection index at 1. Substitute equations (1) and (2) into equation (3). Then we have

$$I_0\cos^2\alpha\sin^2\beta = \gamma^2 I_0\sin^2\alpha\cos^2\beta = I \tag{4}$$

and from this

$$\mathrm{tg}^2\beta = \gamma^2\mathrm{tg}^2\alpha \tag{5}$$

For measured components with determined reflection indices, there must exist a set of angles β and α for which, in this case, the light intensity reaches its greatest value. To find this value, first solve equation (5) for $\cos^2\beta$ and substitute in equation (4); then partially differentiate I with respect to α. Letting $\frac{\partial I}{\partial\alpha} = 0$ to find the maximum value we have

$$\frac{\partial I}{\partial\alpha} = \frac{\partial}{\partial\alpha}\left(\frac{\gamma^2 I_0\sin^2\alpha}{1+\gamma^2\mathrm{tg}^2\alpha}\right) = 0 \tag{6}$$

Expanding the partial differential and simplifying we get

$$\mathrm{tg}\,\alpha = \sqrt{\frac{1}{\gamma}}, \quad \alpha = \mathrm{arctg}\sqrt{\frac{1}{\gamma}} \tag{7}$$

Inserting $\mathrm{tg}\,\alpha$ in equation (5) we have

$$\mathrm{tg}\,\beta = \sqrt{\gamma}, \quad \beta = \mathrm{arctg}\sqrt{\gamma} \tag{8}$$

Insert equation (4), and after simplifying we derive the expression for greatest intensity of light passing through the polarization analysing device.

$$I_1 = I_0\left(\frac{\gamma}{1+\gamma}\right)^2 = I_0 K_1 \quad K_1 = \left(\frac{\gamma}{1+\gamma}\right)^2 \qquad (9)$$

For the most commonly used half-reflecting/half-penetrating (50/50) spectroscopic lens systems, the light intensity is

$$I_2 = 0.25 I_0 \gamma^2 = I_0 K_2,$$
$$K_2 = 0.25\gamma^2.$$

Thus $I_1/I_2 = K_1/K_2 = \frac{4}{(1+\gamma)^2}.$

Therefore when the reflective index of the components being measured R=1, the light intensity is the same as most spectroscopic systems, and when R is very small, its light intensity is close to four times that of the average spectroscopic system. In the common case where R=0.04 (γ =0.2), it is close to three times. Thus the calculations bear out clearly one of the advantages described above.

But, if for each type of reflection index for the surfaces being measured the polarizer and polarization analysing device main section must be positioned according to formula, it not only makes the operation and structure troublesome, it is also actually unnecessary. From the above described calculations and analysis it is seen that as R gets smaller the value for the maximum intensity also decreases. Therefore we set angle β for the lowest commonly used reflection index value R=0.04. Then we fix β at the place determined by the conditions for maximum light intensity (R_0 =0.04) and then do not perform any further adjustments when using it. Then

$$\beta = \operatorname{arctg}\sqrt{0.2} = 24.09^\circ,$$

and the adjustment of angle α is done relying on visual observation to make the contrast of the interference fringe on the projection screen the best possible. Now it still satisfies the light intensity equality conditions of equation (4) (for cases other than R=0.04, however, it does not represent the greatest intensity), therefore:

$$I_3 = I_0 \cos^2\alpha \sin^2\beta = \frac{I_0 \gamma^2 \sin^2\beta}{\gamma^2 + \mathrm{tg}^2\beta} = I_0 \frac{0.1674\gamma^2}{\gamma^2 + 0.2} = I_0 K_3,$$

$$K_3 = \frac{0.1674\gamma^2}{\gamma^2 + 0.2}.$$

We can take K as the decrease after passing through the system and measured components (not calculating loss), the result is as in Figs. 3 and 4.

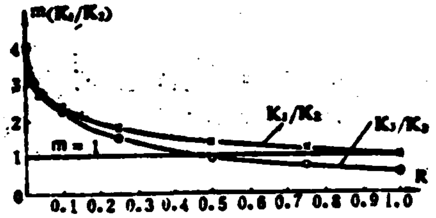


Fig.3

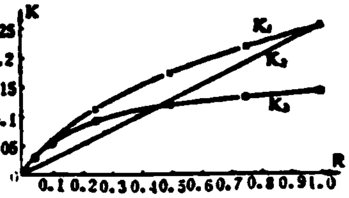


Fig.4

Let m be the increase in light intensity of this system over most spectroscopic systems, then $m = K_i/K_2$, $i = 1, 2, 3$.

From Figs. 3 and 4 we can clearly see that for systems with an R=0.04 determined angle β, the increase coefficient m when $R > 0.47$ is smaller than in most systems, but when the R for a measured component is very small, then we have the greatest intensity of light; basically, it is equal to the light intensity of the maximum light intensity conditions. When R is very large, even though the light intensity is less than for the other two cases, the absolute value for the light intensity is still five times the level for R=0.04. Experiment has also proven that when measuring components for which R=1 the interference fringe is still of sufficient brightness. If we set angle β for the greatest possible intensity of light then the light is sometimes too strong, (nine times the value for R=0.04) and additional reducing devices are required to weaken it. Therefore, if we use appropriate conditions to set the polarization analysing device we can still get the effect of automatic control of light intensity.

4. Regarding the 1/4 Wave-plate

Mica was chosen as the material for the wave-plate. The thickness of the first mica 1/4 wave-plate we used was 6328 Å to within 30μm, but because of differences in place of origin (for natural mica) or production methods (for man-made mica), the variations in thickness were sometimes quite large, and testing the polarizing qualities prior to selection was necessary.

In the convergent light path, as each ray had a different direction relative to the wave-plate, the polarizing qualities also differed for the first wave plate and the intensity of light produced was not uniform. If the relative aperture is smaller than 1:2, the non-uniformity of the light intensity cannot generally be detected [1].

Experiment clearly shows, when parabolic light components are tested, under conditions where the light source does not shine directly on the projection screen, the interference fringe can be clearly seen. Aside from this, the stray light fringe is greatly reduced, aiding measurement.

IV. UNIFORM INCLINATION INTERFERENCE

In this design the rationally selected structural dimensions, optical system and lens grouping parameter allows the instrument to directly make use of an interchangeable objective set (ϕ30, focal length $f' \approx 170$) which measures spherical surfaces advancing uniform inclination interference fringe measurement. For principles in brief see Fig.5. In most precise measurement, a grid board is used to read the number of fringe movements. When making precisely accurate measurements, a highpower microscopic eyepiece is used to show in detail the fractional movements of the fringe.

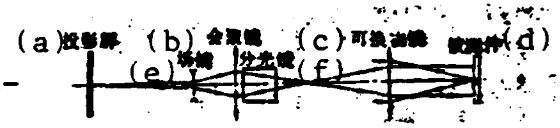


Fig.5 Key:(a)Projection screen; (b)Convergent lens;(c)interchangeable objective;(d) Measured component;(e) Objective;(f)Spectroscopic lens.

With uniform inclination interference, the difference between the degree difference of the inclination angle α and the degree difference of $\alpha=0$ is:

$$d\delta\approx-\frac{\alpha^2}{n}\cdot d.$$

The d here is the thickness of the material. As a result of this, when measuring parallel increments like moving the components to make the fringe contract, movement toward the thick part of the component is clearly shown; if the fringe expands outwardly it shows movement toward a thin area. Additionally, the structure of the instrument also permits use of the method of rotating the components being examined, quickly and accurately locating the wedge angle direction.

When using the uniform inclination interference fringe to measure the parallel increments, the value for the wedge angle is:

$$\theta=\frac{k\lambda}{2nD},$$

the D here representing the horizontal distance the component is moved, while K is the number of changes in the interference fringe when the component is moved. From precise analysis we can see that this instrument, using uniform inclination interference to measure the parallel increments, enables a degree of precision of 0.1 seconds to be easily arrive at, and it measures comparative thickness of interference with great accuracy.

V. QUICK INTERFERENCE FRINGE FORMATION

In order to achieve quick interference fringe formation and operating ease a light spot locating lens 19 (see Fig.1) was inserted into the light path; then the reference light beam and the measured light beam can be seen on the projection screen as two dots of light. Placing the two dots of light in almost the same place and removing lens 19 an interference fringe appears on the projection screen and it again becomes possible to regulate the spacing of the fringe and its direction. Experiment clearly shows the entire process only requires about ten seconds to complete.

Sometimes, because the measured component position deflection is too large, the dot of measured light surpasses the boundaries of the screen, and the dot of light cannot be seen which makes adjustment difficult. For this reason we specially designed rhomboid lenses 11 and 12 (see Fig.1) and placed them in the light path; then the laser beam sends a very thin beam of light through the lens. Because the beam is thin and intense it is very easy to observe whether the light returns on its original path using an added small hole cover. Using the light spots, a rough adjustment can be made, afterwards adjusting it more precisely in the manner described above.

The operator regulates the measured components from the righthand side. If the projection screen cannot be directly observed due to excessive distance, a reflecting prism can be placed on the tube and the interference fringe observed from the side so this machine can be easily operated by only one person.

When high precision measurement requires a photograph, first check the interference fringe, then place the apparatus in a camera obscura and the fringe can be photographed on a 1:1 scale. For this purpose a shutter 23 has been designed in. (See Fig.1)

VI. THE LASER MACHINE

We chose a 1mw single lateral membrane Helium-Neon gas cavity laser chamber for the instrument, but it is not, however, a single frequency one. Most have two vertical membranes. When the degree difference is very large, the interference fringes produced by the two vertical membranes mutually alternate and form blurred fringes. The two vertical membranes' polarizing directions also are usually different, sometimes the angle between the two polarizing directions being close to 90°. Aside from this, because of changes in humidity and cavity length, the frequency also changes producing interference fringe contrast change and fringe displacement. In order to avoid effects adverse to measurement it should be noted that the machine should be turned on and left to sit for half an hour before taking measurements to reduce change in the fringe. The degree difference of the light should be reduced as much as is possible. Making use of the contrast regulating knob, adjust till the fringe is its clearest. If the polarizing directions of the two vertical membranes used are really different only add one of them.

By taking off the cover, the laser tube can be changed easily. All it needs is to take the laser tube portion outside and perfect the adjustment. Make the outside circle machine axis and the laser beam axis parallel at about 10 seconds, concentric at about 0.02mm, then take the portion and put it inside the main body of the machine upon which it can be normally used and need not be otherwise adjusted.

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