

Equivalent Air Layer in Optical System and Teaching Application

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Date of publication (dd/mm/yyyy): 21/01/2022

Abstract – In order to ensure the quality of classroom teaching, strengthen students' understanding of the course teaching contents, so as to make students get better education and cultivate higher quality outstanding talents, based on the author's years of teaching experience and practice, the in-depth explanation and the example analysis have been given through the analysis of the function of flat optical element in optical system and the calculation of equivalent air layer. The students' understanding of the equivalent air layer of planar optical element becomes easier and the related calculation is more convenient. While emphasizing the practicability and effectiveness of knowledge and skills, students' ability to acquire knowledge and use it flexibly can be greatly improved.

Keywords – Optical Instrument, Flat Optical Element, Equivalent Air Layer, Reflecting Prism.

I. INTRODUCTION

The optical planar elements are widely used in optical engineering, such as prisms, parallel planar plates, planar reflectors, optical flats, optical wedges, reticles, linear scales, optical disc substrates, filters, wave plates, gratings, compensating plates, frequency multipliers, liquid crystal light screen planes and so on. The sizes from $\phi 1\text{mm}$ to $\phi 1000\text{mm}$ or more, the materials are mainly optical glasses or optical crystals^{[1]-[5]}. The optical parallel plates or reflection prisms are often placed in the optical path of optical system design especially, which often involves the calculation of the optical aperture size of optical elements^{[6]-[9]}. In an optical system containing an optical parallel plate or a reflection prism, the concept of the equivalent air layer to simplify the calculation needs to be introduced to easily calculate the projected height of light on the plate or prism, and meanwhile easy to calculate the optical aperture size of the optical element adjacent to the optical parallel plate or prism. However, in the process of engineering optics teaching, students lack perceptual understanding of virtual abstract equivalent air layer and have great difficulties in learning^{[10]-[12]}. In order to help students understand easier, the concept of equivalent air layer and its typical application is analyzed below.

II. EQUIVALENT AIR LAYER OF A PARALLEL PLATE

It is known that the optical parallel plate is an optical element with non-focal-power, whose focal power is 0 and its transversal magnification is 1. The object becomes positive image after optical parallel plate imaging. The object and its image are located on the same side of the optical parallel plate, and the image scale will not zoom in and out, and the virtual and reality of object and image are opposite^{[13]-[15]}.

The direction of emergent light refracted by optical parallel plates in the optical system is unchanged, but it doesn't absolute coincide with the incident light. And an axial displacement and a vertical displacement will occur^{[13]-[15]}. The axial displacement $\Delta L'$ has a great impact on the calculation of optical axis direction, which is expressed as follows:

$$\Delta L' = d \left(1 - \frac{\tan I_i'}{\tan I_1} \right) = d \left(1 - \frac{\cos I_1}{n \cos I_i'} \right) \quad (1)$$

In formula, d is the optical parallel plate thickness, n is the plate refractive index, I_1 is the incidence angle of light on the first face of the plate, and I_1' is the refraction angle of light on the first face of the plate. As shown in figure 1.

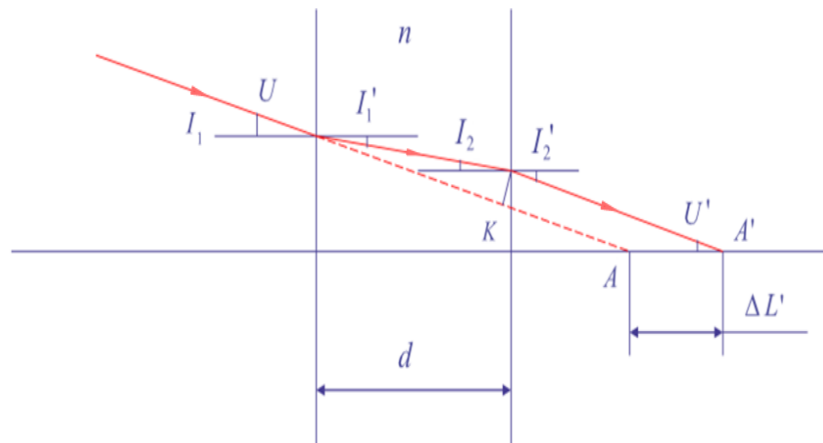


Fig. 1. Optical parallel plate imaging.

It can be seen that when the broad optical beams are imaged through the optical parallel plate, the axial displacement $\Delta L'$ varies with the incident angle I or aperture angle U . That is, the light rays of different aperture from the same point on the optical axis have different points of intersection with the optical axis after passing through the optical parallel plate. The concentric light beam becomes a non-concentric light beam, so the optical parallel plate imaging is imperfect.

But when the paraxial light ray is imaged through an optical parallel plate, the incident angle I_1 is small, and its axial displacement is approximately to:

$$\Delta L' = d \left(1 - \frac{1}{n} \right) \quad (2)$$

Obviously, the axial displacement $\Delta L'$ of the paraxial region is independent of the incident angle or aperture angle, so the optical parallel plate is considered to be perfect imaging in the paraxial region.

As shown in figure 2, a light emitted from the lens L becomes PS_2' after passing through the optical parallel plate $CDEF$. Move left the emergent plane FE of the parallel plate and the emergent light PA_2' for $\Delta L'$ along the optical axis. Then EF and MN , PA_2' and QA_1' coincide respectively. This indicates that the ejection of light at the point P on the plane EF after passing through the parallel plate $CDEF$ is exactly the same as the point Q on the plane MN after the light pass the air layer $CDMN$ without refraction (all four aspects are identical: (1) Projection height of the light on the incident plane of the optical elements; (2) Propagation direction of the outgoing light; (3) Distance between the outgoing plane and the intersection of the light on the optical axis; (4) Size of the image). The difference is that the light passing through parallel plate $CDEF$ is refracted on both planes of the CD and EF , but without refracting through parallel plate $CDMN$. The light is straight through $CDMN$. So the $CDMN$ is called the equivalent air layer of the parallel plate $CDEF$. If the thickness of the equivalent air layer is \bar{d} . The \bar{d} can be calculated from the figure 2.

$$\bar{d} = d - \Delta L' = \frac{d}{n} \quad (3)$$

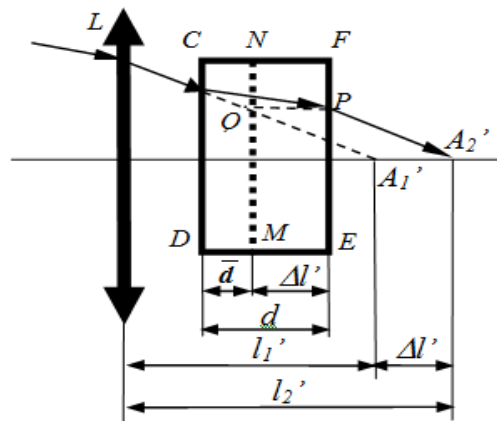


Fig. 2. Equivalent action of optical parallel plate in light path.

It can be seen that appropriate using of equivalent air layers is very beneficial in optical system design calculation. Only calculate the image position A_1' without the optical parallel plate and then move an axial displacement $\Delta l'$ along the optical axis, the actual image position A_2' with optical parallel plate will be obtained. As shown in figure 2, the image distance of l_2' can be obtained directly from the figure without imaging calculations.

$$l_2' = l_1' + \Delta l' \quad (4)$$

III. APPLICATION ANALYSIS OF EQUIVALENT AIR LAYER

When the reflection prism is placed in an optical system, it is equivalent to an optical parallel plate during calculation. That is, the reflection action of the prism is not considered. It amounts to regard the prism as an optical parallel plate adding to the light path^{[13]-[15]}. The action is to straighten the light path in the reflection prism to replace the light path between the two refracted planes of the reflection prism. So the role of the optical parallel plate in the optical calculation is crucial.

For example, an optical system objective lens with a focal length of 125mm has an optical aperture diameter of 30mm and the size of its image is 5mm. Place a right-angle prism at 75mm behind the objective lens (the glass refractive index is 1.5). If all rays of light through the objective lens participate in the imaging, the distance of the image plane away from the outgoing plane of the prism, and the aperture diameter of the beam incoming and outgoing the prism plane can will be calculated by using the parallel plate equivalent air layer. The analysis is made as follows.

A. The Distance Of The Image Plane Away From The Ray Outgoing Plane Of The Prism

Since the object of the telescopic objective lens is located at infinity in theory, its image plane lies on the focal plane of the image side of the objective lens. As shown in the Figure 3, according to the known conditions given, it can be seen that without the prism, the image plane $A_1'B_1'$ is located in the focal plane (Position F') of the image side of the objective lens. When placing the right-angle prism, the image plane is shifted to the right for a distance of $\Delta l'$ to position S' , that means the image plane is $A_2'B_2'$. The right-angle prism CDE expands into a parallel flat plate $CDEH$ during the optical calculation, and its equivalent air layer is parallel flat plate $CDMN$ in figure 3. Therefore, all imaging beams after through the objective lens can be regarded as located in a cone $L_1L_2B_1'A_1'$ with a height of 125mm and a diameter of 30mm and 5mm respectively during calculation.

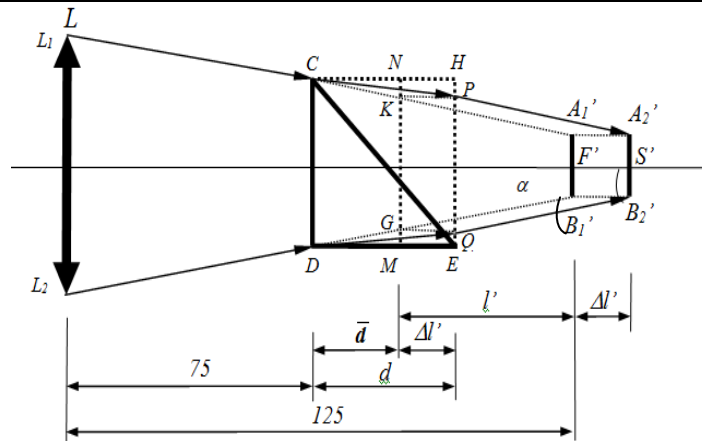


Fig. 3. Application of reflection prism and equivalent air layer in optical path.

After the right-angle prism expands into an equivalent parallel plate in the previous example, the plate thickness of the prism is equal to its optical aperture size. That is: $d = \overline{CD} = 15\text{mm}$. Thus the equivalent air layer thickness of the optical parallel plate is $\bar{d} = \frac{d}{n} = 10\text{mm}$

As shown in the Figure 3, the distance of the image plane away from the ray outgoing plane of the prism is equivalent to the l' . That is $l' = 125 - 75 - \bar{d} = 40\text{mm}$

B. The Apertures of the Ray Incoming Surface and Outgoing Surface in the Prism

So, the optical aperture size \overline{CD} of the light incident plane of the prism is $\overline{CD} = 5 + 2 \times (125 - 75) \cdot \tan \alpha = 5 + 100 \times \frac{30-5}{2 \times 125} = 15\text{mm}$

Therefore, the optical aperture size \overline{PQ} of the light outgoing plane of the prism is $\overline{PQ} = \overline{KG} = 5 + 2 \times l' \cdot \tan \alpha = 5 + 2 \times 40 \times \frac{30-5}{2 \times 125} = 13\text{mm}$

IV. SUMMARY

From the above analysis, it can be seen that the application of equivalent air layer of optical parallel plate simplifies the originally complicated optical calculation which also helps students understand easier. It is widely used in optical system ^{[16]-[19]}. But at the same time, students should also understand that the concept of "equivalence" in the equivalent air layer is not exactly equal. It only means that when a same incident light passes through an optical parallel plate, the position of the image surface relative to the second surface of the optical parallel plate is equivalent to that of the object surface relative to the second surface of the equivalent air layer, which is specifically shown in the light passes situation is the same state in the following four aspects: (1) Projection height of the light on the incident plane of the optical elements; (2) Propagation direction of the outgoing light; (3) Distance between the outgoing plane and the intersection of the light on the optical axis; (4) Size of the image. The difference lies in: (5) There is an image surface displacement after the same light passes through the parallel plate, but the equivalent air layer does not; (6) The parallel plate has aberrations, but the equivalent air layer does not. Therefore, when calculating an optical system with an optical parallel plate, the

plate is first simplified into an equivalent air layer to calculate the imaging position, and then the image is moved along the optical axis by an axial displacement to obtain the position of the final image. It can be widely used in optical design and computing.

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