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EXPERIMENTS ON FRESNEL DIFFRACTION BY A NARROW TRANSPARENT RING IN AN OPAQUE SCREEN

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THE luminous diffraction spot in the middle part of a geometric shadow, which is typical (for coherent illumination) of the Fresnel diffraction pattern of a sphere or disc, can also be used in the case in which a narrow annular cut (transparent ring) in an opaque screen is used as the object.

If the illumination is not coherent over the entire extent of transparent ring (and it is practically impossible to produce coherent illumination of the latter if the ring diameter is appreciable), then, as for diffraction from a sphere or a disc, the thin annular interference structure of the picture vanishes. Nevertheless in this case (in contrast with the case of a sphere or disc) a picture appears on the observation screen B (Fig. 1a), which has a sharply expressed annular structure. The latter is brought about by the interference effect on the individual small azimuthal elements of the transparent ring (over the extent of each of which the illumination remains coherent) in combination with the effect of summation of the intensities of the beams diffracted from the different elementary parts.

This picture has its own system of broad secondary diffraction rings which lie outside and inside the main ring, and the periodicity of the diffraction rings is determined not by the diameter of the transparent ring D but by its breadth d.

For certain specific positions of the screen B the beams (diffracted from the different elements of the transparent ring) overlap in the central part of the picture. This corresponds to a secondary maximum of intensity of a certain order k. In this case, as the result of summation of the intensities of the overlapping beams, a bright central diffraction spot of k-th order is produced. With a sufficiently thin transparent ring (0.004—0.005 cm) it is possible to use a comparatively weak light source and obtain a diffraction picture with a clearly distinguishable central spot of such a nature from a ring of diameter 4—5 cm on a screen which is only several tenths of a meter away from it!

If one uses in place of the small light source an extended luminous object, then at definite positions of the observation screen a diffraction picture of the source appears in the central part of the picture, inasmuch as each small luminous part of the latter is shown on the screen in the form of the central diffraction spot corresponding to it.

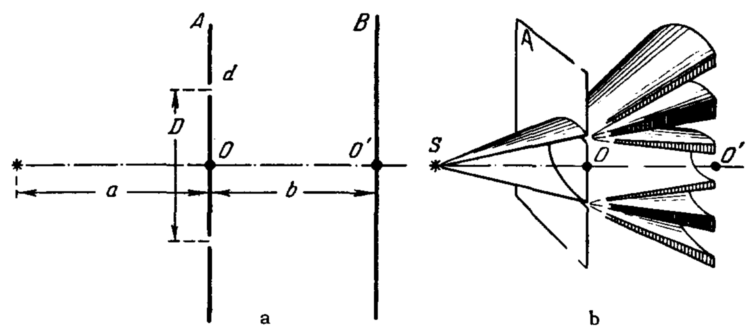
The ability of the ring to create a diffraction picture gives grounds for applying to it the concept of the focal length. It follows from what was pointed out above, however, that the ring is characterized not by a single value of F, but by a whole set of focal lengths F_k. Calculations lead to the formula

$$F_k \approx \frac{1}{2k+1}\frac{Dd}{\lambda} \quad (k=1, 2, 3, \ldots). \tag{1}$$

On the basis of Eq. (1), one can draw some conclusions on two different features of the Fresnel diffraction case considered. First, the ring possesses a significant chromatic aberration (the sign of which is opposite to the sign of the chromatic aberration of a simple converging lens).

Second, for sufficiently small values of d the focal length F_k is comparatively small, and by means of such a ring, one can in practice obtain a diffraction picture of a luminous object for distances between the parts of the apparatus that are smaller by a factor of ten than in the case of a sphere (or disc) of the same diameter as the ring.

The demonstration possibilities of the method can be greatly enhanced by using an object in the form of two concentric transparent rings of the same width. In this case the form of the diffraction picture changes as the result of interference of beams diffracting from the different rings. If the width d of each ring amounts to 0.004—0.005 cm, while the distance c between their



a b

FIG. 1

midpoints, measured along the radius, exceeds this quantity only several fold, then in practice the total overlap of the beams diffracted from the corresponding azimuthal elements of the rings takes place even for small distances from the second ring to the observation screen. If the overlapping beams are coherent, the interference produces a system of narrower interference rings in the region of the principal diffraction ring, as also in the region of the secondary rings. Essentially the experiment represents in this case the visualization of the classical experiment of Young. However, because of the axial symmetry, the arrangement is characterized by a number of special features which are useful for demonstration of the phenomenon.

In order that the interference rings possess identical contrast at different places, one must use a luminous aperture of circular shape as the light source. The dimensions of the latter are limited by the coherence condition. However, these limitations are unimportant for small values of c.

If the illumination of the apparatus is with white light, the picture on the observation screen takes the following form: along the center line of the principal diffraction ring there is located a narrow colorless zero-order interference ring; adjoining from the inside and outside are colored interference rings of successive orders. The number of these rings within the limits of the principal diffraction ring depend on the ratio c/d. This part of the picture is of most interest, inasmuch as the major part of the luminous flux passing through the apparatus is distributed in the region of the principal ring, while the interference rings generated here have a low order of interference and can be observed in white light.

Because of the axial symmetry of the arrangement, it is not difficult to obtain radial "compression" of the picture, and the principal ring can be made to occupy a smaller area in the central part of the picture, so as to increase the illumination. For this purpose one must place a simple converging lens next to the object (the double ring) so that the principal optical axis of the lens coincides with the axis of the apparatus. The change in the position of the interference rings observed in this case can be regarded as a consequence of the appearance of an additional path difference of the interfering rays, brought about by change in the thickness of the lens both in the transition from one transparent ring to the other and within the width of each ring.

Now the form of the picture on the observation screen depends to an essential degree on the screen position. For example, if the screen is moved away so that the internal boundary of the principal diffraction ring contracts to the central point, the middle part of the picture is filled with interference rings of first order, while an increase in the distance from the center first decreases the order to zero and then begins to increase it.

Demonstration of the experiments. For the narrow ring of regular form and of suitable uniformity in width, which allowed us to obtain satisfactory results, we used in our experiments an annular slit made by the point of a needle moved along a circle on a smoked glass plate after wetting of the lamp-black layer with alcohol and drying.

The photographs of the diffraction pictures of the filament of an incandescent lamp shown in Fig. 2 were obtained by means of a ring of diameter $D \approx 4$ cm and width $d = 0.004$ cm.

A diffraction object in the form of a system of two concentric transparent rings very close in diameter and identical in width was prepared in the same fashion. The diffraction pictures shown in Figs. 3a and 3b were obtained by means of a twin ring with the following diameters: $D_1 \approx 4.8$ cm, $C_1 \approx 0.014$ cm, and $d_1 \approx 0.005$ cm. In Fig. 3c is shown a photograph of the diffraction picture of a twin ring with larger values of D and C.

For an experiment with a single ring, the apparatus was arranged as shown in Fig. 1. The picture was viewed on a frosted glass B which was so located that the image of a luminous object the required order was seen quite sharply. The first-order images produced when working with "white" light, have a clearly pronounced coloring (brought about by chromatic aberration of the ring), which decreases upon displacement of the frosted glass B. This coloring becomes weaker for very high orders, because of the greater overlap of the images produced in a given plane by the different spectral components in different orders.

The pictures were photographed without the use of a filter. The ground glass was first placed in such a

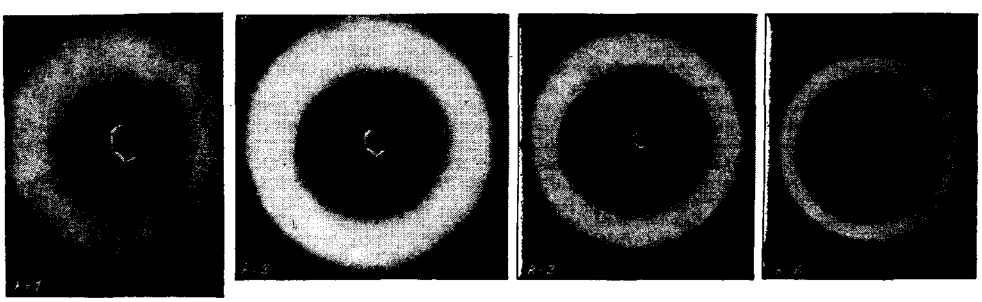


FIG. 2

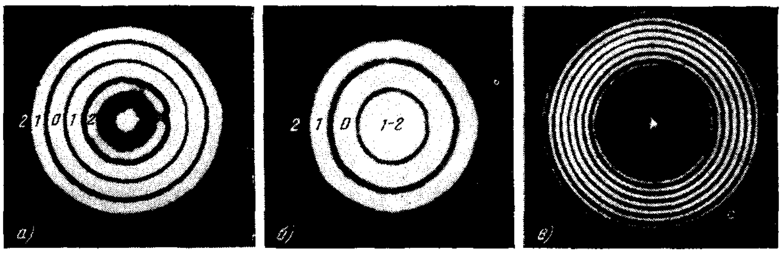


FIG. 3

plane that the image had a coloring corresponding to the long wavelength part of the visible spectrum. After this, the glass screen was removed and replaced by a flat holder loaded with isopanchromatic film of sensitivity 90 GOST units. Contact prints were obtained from the negatives, with the dimensions of the diffraction pictures on each obviously coinciding with the dimensions of the picture on the screen B. In Fig. 2 are shown photographs of the images of a simple object—the filament of an incandescent light—in different orders ($k = 1, 2, 3, 6$). The distance a in all these experiments was kept constant at 220 cm, the distance b was varied and amounted to $b_1 \approx 135$ cm, $b_2 \approx 70$ cm, $b_3 \approx 40$ cm, $b_6 \approx 20$ cm, respectively. All the photographs were taken with an exposure $t = 5$ sec.

To obtain a sharp diffraction picture by means of the double rings in the arrangement of Fig. 1, it was convenient to introduce a converging lens. In our experiments, we used a lens with a focal length of 70 cm, which was placed behind the double ring. The light source in this experiment was a circular aperture illuminated by a motion picture projector lamp. To obtain greater contrast, the light source used for photography was covered with a red glass. (For visual observation of the picture the use of a light filter is undesirable.) The picture was photographed in these experiments in the same way as before.

In Fig. 3a is shown a photograph of the picture obtained for distances a′ (from the source to the lens) and b′ (from the lens to the photographic plate) equal to 100 and 90 cm, respectively. The photograph shows clearly the interference rings of zero and first orders. The weak second-order outer ring is barely noticeable while the inner second-order interference ring is seen very clearly. The inadequacies of the picture, brought about by the roughness of the boundaries of the diffraction object, are clearly noted here. The spot in the middle part of the picture arises as a result of the concentration of flux corresponding to the second diffraction ring of first order. The photograph in Fig. 3b was obtained for distances a′ and b′ equal to 100 and 150 cm, respectively. In this photograph the outside second-order interference ring is also seen weakly, but it is better than the one in the previous case. The central part of the picture is the result of overlapping of the fluxes corresponding to the internal interference rings of first and second order. Upon further increase of separation of the screen, the picture is "turned inside out."

Figure 3c shows a photograph of the picture from another (less successful) double ring, which has large D and C. This picture corresponds in its structure to what is shown in Fig. 3a. However, inasmuch as the ratio c/d is larger in this case, than in the previous one ($c_2 \approx 0.03$ cm, $d_2 \approx 0.005$ cm), the region of the principal diffraction ring contains a correspondingly larger number of interference rings.

The experiments described differ from other experiments on Fresnel diffraction not only by the fact that they call for smaller distances between the parts of the apparatus, but also by the fact that, in practice, no adjustment of the apparatus is necessary to obtain a sharp diffraction picture. The only difficulty that calls for some skill is in the preparation of the diffraction objects in the form of a single transparent ring of sufficiently small and constant width (and even more so for a double ring).

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Translated by R. T. Beyer