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Diffraction on an Aperture Located Between Media with Different Refractive Indices

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Abstract. Fraunhofer diffraction of a plane electromagnetic wave is considered on an aperture in an opaque screen located between two media with different refractive indices, as well as between vacuum and refractive material medium, in the presence and absence of birefringence. The angular distribution of the intensity of diffracted radiation is determined. The case of an anisotropic medium is also considered. Some peculiarities of diffraction in this formulation are revealed, in particular, including the nonreciprocity phenomenon. It is shown that the intensity of the diffracted wave depends on the refractive index of the medium into which the electromagnetic radiation penetrates. This leads to the possibility of creating new optical elements, the scope of which, in particular, can be the creation of alternative schemes for the light energy storage devices. An experimental study of the nonreciprocity phenomenon was carried out.

Keywards: Fraunhofer diffraction, nonreciprocity phenomenon.

1. Introduction

The diffraction of electromagnetic waves on an infinite screen with a slit or a round hole has been considered in optics in the case when a vacuum is located in front of the screen and also after the screen [1,2]. In material media the diffraction phenomenon is usually considered in situations where it is caused not by the limitation of the wave front (diffraction from the edges of slits or openings), but mainly by the periodicity of the inhomogeneities of the medium in which the wave propagates [3-5].

In [6], the Fraunhofer diffraction of a plane wave by an infinite slit was considered, when both the sides of the screen with a slit were occupied by media with different values of the refractive index (one of them may be a vacuum). In particular, it was shown that in such a situation there is a nonreciprocity of the passage of an electromagnetic wave through the slit. This phenomenon is of great practical importance in the creation of optical systems that have nonequivalence of mutually opposite directions of the transmission of electromagnetic waves [7-8].

In the present work, we consider diffraction by a rectangular slit and circular hole in a metal screen, the both sides of which are occupied by media with different values of the refractive indices.

2. The intensity of the electromagnetic wave diffracted from air into a dielectric medium through a slit in the screen

Let us consider the normal incidence of an electromagnetic wave on an opaque screen with a slit width **a** (Fig. 1). The wave intensity in the angular region $(\theta, \theta + d\theta)$ is determined by the formula [9]:

$$dI = \frac{I_0}{2\pi} \times \frac{\sin^2(ka\theta)}{(ka\theta)^2} d(ka\theta) \tag{1}$$

where I_0 is the intensity of the incident wave, θ is the angle of deviation of the diffracted wave from the direction of the normal to the screen and $k = \frac{\omega}{c} n$.

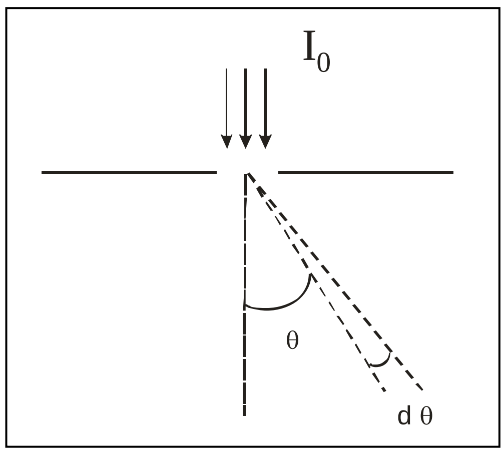


Fig. 1. Scheme of diffraction of the electromagnetic wave on a round hole.

The total intensity I of the diffracted wave is given by

$$I = \frac{I_0}{2\pi} \times \int_{-\pi/2}^{\pi/2} \frac{\sin^2(ka\theta)}{(ka\theta)^2} d(ka\theta). \tag{2}$$

The integral in this expression is expressed in terms of the function $Si(x)$. Figure 2 shows the dependence of I on k showing that with increasing k the intensity of the wave behind the slit also increases.

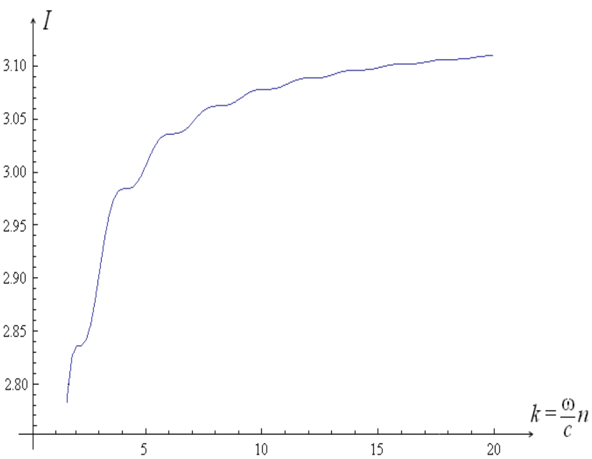


Fig. 2. The dependence of the total intensity on *k*.

The increase of the intensity with an increase in the refractive index is understandable: for shorter wavelengths, the more intensity passage through a narrow gap (commensurate with λ). Mathematically, the increase in the intensity I with an increase in the refractive index can be understood as a result of broadening of the integration range in formula (2). Fig. 3 shows the dependence of the function $\sin^2(\theta)/\theta^2$ on θ. The value of the integral over this function is equal to the area of the dashed region. Introducing a new integration variable $x = ka\theta$, the integration limits become -$\left(\frac{\omega}{c} na \frac{\pi}{2}\right)$ and $\left(\frac{\omega}{c} na \frac{\pi}{2}\right)$, and the integration range increases with increasing n.

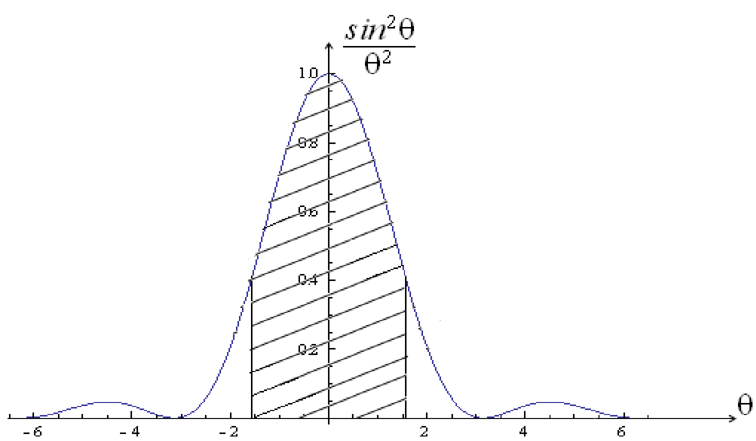


Fig. 3. The dependence of the integrand $\frac{\sin^2(\theta)}{\theta^2}$ on θ

3. The experimental part

We have experimentally investigated the diffraction passage of electromagnetic waves through a narrow slit cut in a metal plate mounted between two dielectric plates of two materials with different refractive indices. For the convenience of measurements, an electromagnetic radiation source in the range $40-50GHz$ was used. The experimental design is shown in Fig. 4. The slit 3 with the width of $5mm$ is formed in the metal (brass) plate having $1mm$ thickness. The plates 2 and 4 of teflon (polytetrafluoroethylene) and plexiglas (polymethylmethacrylate) of the same thickness (equal to $3.5mm$) were attached to the metal plate from different sides. Directly at the output of such a three-layer structure, the radiation detector 5 was placed. Next, the analog signal from the detector, converted to the digital one by means of ADC 6, is processed by computer.

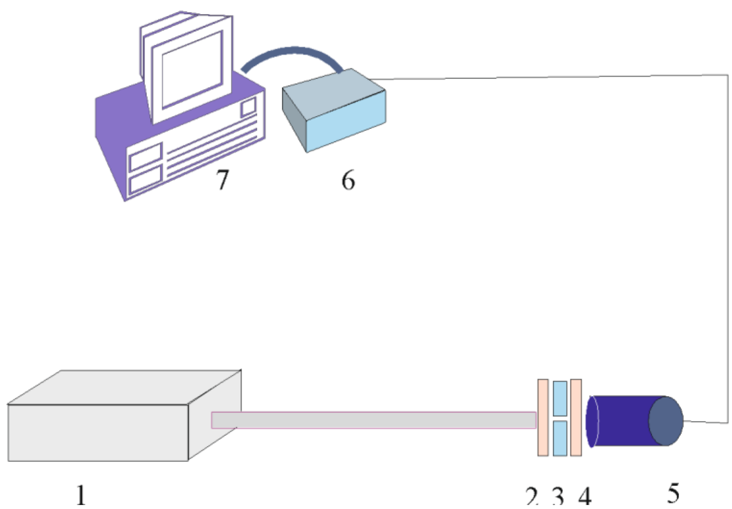


Fig. 4. The experimental setup. 1 - electromagnetic radiation generator, 2 and 4 - plates of dielectric material, 3 - metal plate with a rectangular slit, 5 - radiation detector, 6 - ADC, 7 – computer.

Note that the range of refractive indices of amorphous polymers is much smaller than that for traditional optical glasses and reaches up to $n=1.70$ [7]. Accordingly, the value of n for PMMA is 1.51. For polymeric materials, a significant decrease in the refractive index is possible by introducing fluorine atoms into the molecule of the initial monomer. Fluorinated polymers have small refractive indices $(n \leq 1.4)$ [8]. In the case of teflon used in the experiment, n is in the range $1.35-1.38$ [9].

For a slit of $5mm$ wide, the measurements showed the difference in the amplitude of the transmitted signal depending on the arrangement of the teflon and plexiglas plates (Fig. 5).

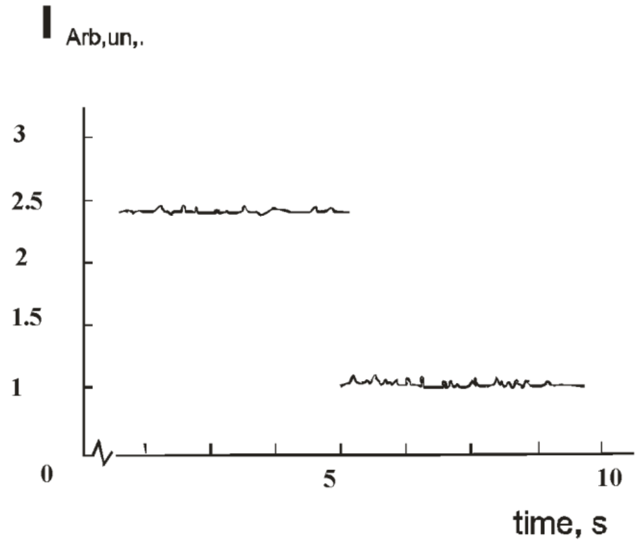


Fig. 5. Dependence of the amplitude of the transmitted signal on the change in the arrangement of teflon and plexiglas plates relative to the slit. **a**: plexiglass-slit-teflon, **b**: teflon-slit-plexiglass. The microwave generator frequency was 41 GHz and the slit width was 5 mm.

As it is seen from Fig. 5, for the case of radiation passing in the teflon-slit-plexiglas system, the amplitude of the recorded signal is 2.5 times different from the amplitude for the reverse sequence of the same dielectric plates. This experimentally confirms the nonreciprocity of the passage of the electromagnetic wave through the gap in the described optical system.

4. Diffraction on the round hole

The calculation of the influence of the refractive index of the medium for the radiation diffracted from the round hole with radius a is based on the well-known formula [9]

$$I = I_0 \int_{-\pi/2}^{\pi/2} \frac{J_1^2(ak\theta)}{\theta^2} d\theta \ , \tag{3}$$

where I_0 is the intensity of the incident wave, θ is the angle of deviation of the diffracted wave from the direction of the normal to the screen, $J_1(x)$ is the Bessel function. Comapred to the case of vacuum behind the screen, in the case of a material medium, in formula (3) the expression for the modulus of the wave vector k is changed by the presence of the refractive index n.

The integral in (3) is expressed in terms of the Bessel functions $J_0(\pi ak/2)$ and $J_1(\pi ak/2)$. Fig. 6 presents the dependence of I on a given in the wavelength λ. As seen, with increasing radius of the hole, the wave intensity behind the slit increases, and the shape of the curve depends on the value of the refractive index n.

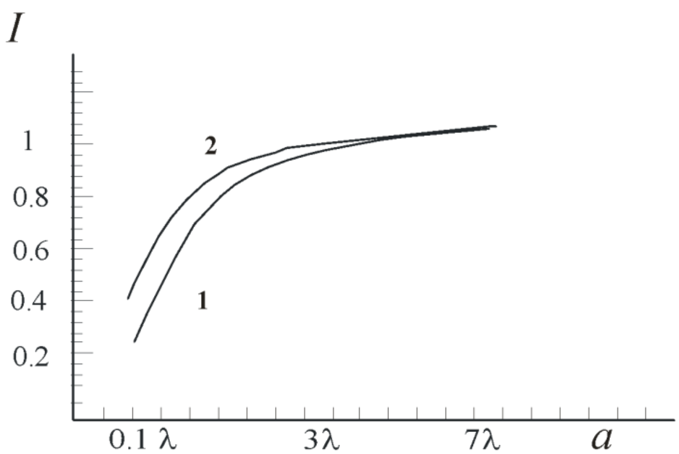
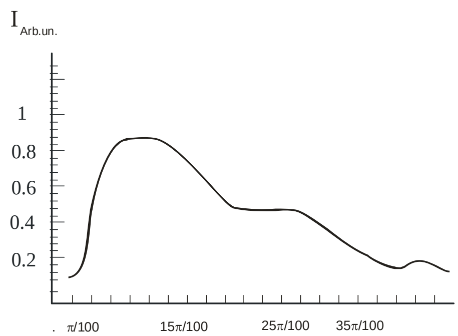
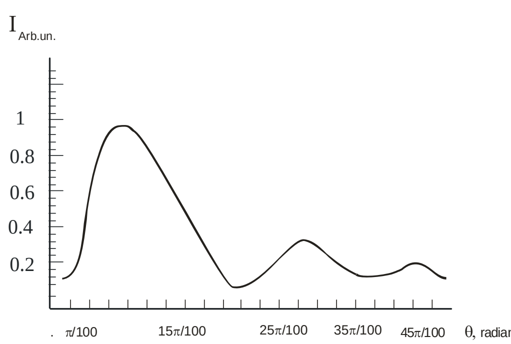


Fig. 6. Dependence of the intensity of the diffracted wave *I* on the radius of the circular hole. The curve 1 corresponds to the case n = 1 and the curve 2 - to the case n =2.

From (3), we also expect a change in the angular distribution of the intensity of the diffracted wave with a change in the value of the refractive index. Fig. 7 shows the calculated dependences of the angular distribution of the intensity of the diffracted wave for various values of the refractive index, in the case where the medium behind the hole is isotropic.



a



b

Fig. 7. Angular distribution of the diffracted wave intensity for the (a) n = 1 and for the (b) n = 2

As it is seen from Fig. 7, a noticeable change in the angular distribution of the intensity of the diffracted wave is observed with a change in the refractive index. The distance between the interference rings is controllode by the choice of the refractive index for the neighboring medium.

Another case of diffraction is realized when a uniaxial anisotropic medium with an optical axis parallel to the plane of the screen is placed behind the screen with an aperture. In this case, at small diffraction angles, formula (3) can be written separately for the ordinary and extraordinary waves assuming that the change in the refractive index for the extraordinary wave upon its deviation from the perpendicularity to the optical axis can be neglected:

$$\begin{aligned} dI_o &= I_{oo}\frac{J_1^2(a\frac{\omega}{c}n_o\theta)}{\theta^2}d\theta \\ dI_e &= I_{oe}\frac{J_1^2(a\frac{\omega}{c}n_e\theta)}{\theta^2}d\theta \end{aligned} \tag{4}$$

Thus, in this case, when the demonstration screen is located behind the hole, it will be possible to observe a complex diffraction pattern consisting of two sets of diffraction rings formed separately by ordinary and unusual waves. As a result, the detailed photometry of the obtained diffraction pattern makes it possible to analyze the optical anisotropy of various media using a simple optical scheme. Note that the study and analysis of anisotropic media using standard refractometers is a rather complicated technical problem.

5. Conclusion

Our assumption on the nonreciprocity of diffraction of an electromagnetic wave by a aperture between two media with different refractive indices is experimentally confirmed. The experiments were carried out for the millimeter range. As dielectric media on different sides of the slit polytetrafluoroethylene (teflon) and polymethylmethacrylate (plexiglass) were used. Numerical calculations also confirm the presence of nonreciprocity in such an optical system. The phenomenon of optical nonreciprocity considered in this work can be used to develop new optical elements, as well as energy storage devices.

The phenomenon of diffraction by a round hole in a screen located between two media differing in their refractive indices is also studied. A numerical calculation of the intensity of the diffracted wave in this optical system is carried out. The peculiarities of the diffraction pattern are studied depending on the refractive index of the medium, including the case of a birefringent medium.

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Conflict of Interest

There is no conflict of interest.

Author Contributions

A.R. Mkrtchyan, H.S. Eritsyan, A.L. Margaryan, carried out theoretical calculations, A.A. Lalayan invented and developed the experiment and carried out theoretical calculations

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