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Diffraction pattern by rotated conical tracks in solid state nuclear track detectors

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ABSTRACT

The method for determination of diffraction pattern for irregular 3D objects with application on rotated conical tracks in solid state nuclear track detector (SSNTD) wasdescribed in this paper. The model can be applied for different types of the diffraction (Fresnel, Fraunhofer) and arbitrary shapes of the obstacle.

By applying the developed model on conical tracks it was fond that diffraction pattern strongly depends from radius, length and rotation angle of the conical tracks. These dependences were investigated in this paper and results can be applied for determination of inner tracks structure via diffraction pattern.

1. Introduction

The main subject of investigation in Optics is propagation of light through the slits and near obstacles, whose dimensions are order of magnitude of wave length of the light [1]. Due to propagation of the light through such objects, the diffraction of the light will be appeared. According to the form of wave front, there are two types of diffraction: Fresnel (regarding to spherical wave front) and Fraunhofer (regarding to the plain wave front). In the case of Fresnel diffraction, light intensity distribution is observed on the screen which is on the short distance behind object, while at Fraunhofer diffraction, the screen is on the large distance [2].

The occurrence of diffraction can be explained by Huygens–Fresnel principle of propagation of the light wave. Many papers are devoted to diffraction on the slits of certain forms and shapes [3–10]. The analytical expression for light intensity distribution, in form of Bessel functions, Fresnel integrals or by using Fast Fourier Transformation (FFT), can be obtained for specific cases of slits (circular, rectangular, elliptical).

According to our knowledge, there are few papers devoted to diffraction of light on 3D objects. Fraunhofer diffraction has been studied for the slits in the shape of the right cone [11] and the half sphere [12] which are located in planparalel plate. In both cases, the distribution of the intensity of light is obtained via Bessel functions. On that basis, influence of the dimensions of the slits on diffraction pattern is considered. The aim of these works was to apply that analysis on studying of shapes and dimensions etched tracks of nuclear solid state detectors (SSNTD) originating from the heavy charged particles, formed normal to the detector surface. The method described in those papers presents a good approach to determine track parameters.

The detected particles are emitted in different directions and their latent tracks are oriented randomly within the detector. Some tracks will be etched from the point where the particle entered detector, in the direction of the particle motion-direct etching, while other tracks will be etched from the point where the particle was stopped- reverse etching [13–15].

It is very important to investigate diffraction pattern of the light which penetrate through the conical tracks created under some angle in respect to surface of detector, because larger fraction of detected particles is not oriented normal to the surface. The objective of this paper is to expand the model described in [11,12] for rotated conical tracks. The track formed in that way has irregular shape and its projection on the plane of detector plate is not regular surface. For that reason, it is not possible to derive analytical expression for light intensity distribution and numerical model was developed in this paper.

2. Theoretical analysis

The amplitude of oscillation of the electric field of light at point P, caused by secondary wave sources, is proportional to the segment of surface wave front dS and inversely proportional to the its distance r to the point P [1,2]:

$$E_P = \iint_S -\frac{i}{\lambda} a(\beta, \gamma) \frac{1}{r} E e^{i\left(\omega t - \vec{k}\vec{r}\right)} ds \tag{1}$$

The integral shown in Eq. (1) is called a Fresnel–Kirchhoff

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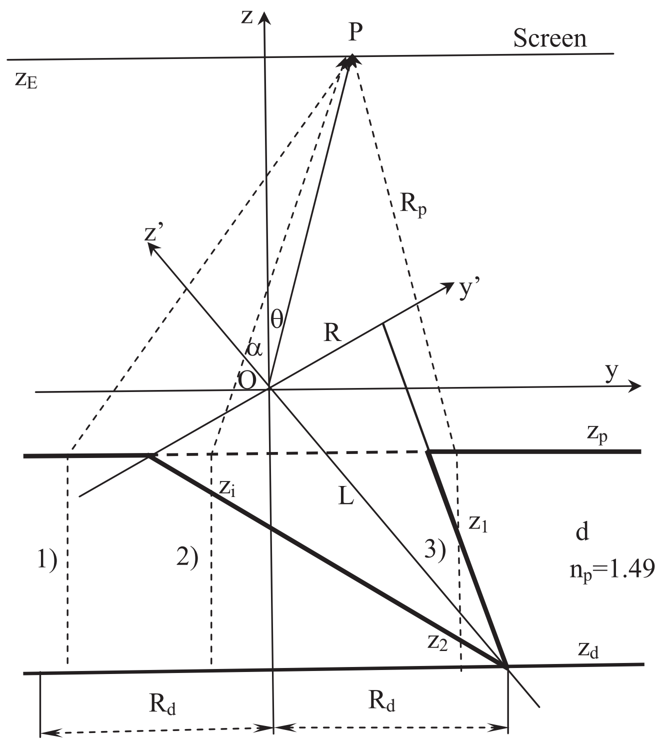

Fig. 1. The geometry of plates, slits and screen.

integral. In the integrand, E is the electric field intensity of light wave on the surface of the wavefront dS, ω is the angular frequency and λ is the wavelength of light.

The strength of electric field of the wavefront depends on the angle β, between the outer normal to the wave surface dS and the direction r from the element dS to the point P, and the angle γ which is the angle between the normal vector of elementary surface dS and the incoming direction of the light wave. The factor $a(\beta,\gamma)= 0.5(\cos\gamma+\cos\beta)$ is called the inclination factor. If on the segment of elementary surface dS is coming plane light wave, then γ is equal to 0 and if the point P is on a large distance of segment dS (Fraunhofer diffraction) then $\beta=0$. For an incident plane wave front and Fraunhofer diffraction, the inclination factor is approximated by unity.

The geometry of the light passing through the rotated cone, with the screen on which diffraction pattern is created, is shown in Fig. 1. The system consists of a planparalel plate with refractive index $n_p=1.49$ and thickens d. The coordinate system $xOyz$ is set in that way that x and y axes are parallel to the planparalel plate, while z axis is perpendicular to the plate surface, with positive direction towards the screen. Inside the planparalel plate is a slit in form of rotated cone. The radius of the cone is R and its height is L. The coordinate system $x'Oy'z'$, in which the cone is right (not rotated) along the z' axis, is rotated by an angle α around x axis (x and x' axes coincide). The angle α is the angle of rotation of the cone inside the planparalel plate.

If $\alpha=0$, the cone is also right (not rotated) and cone basis is lying on the upper surface of the planparalele plate, which belongs to xOy plane. The thickness of planparalel plate is then equal to the height of the cone ($d=L$) and lower plane of plate has a coordinate $z_d=-d$, while $z_p=0$. This geometry is the same as discussed in [11].

If $\alpha>0$, then the base of the cone intersects the plane xOy at the same angle α. In this case, the lower plane of plate has a coordinate $z_d=-L\cdot\cos(\alpha)$ and the upper surface of planparalele plate does not belong to the plane xOy, but is defined by the lowest point of the cone basis, $z_p=-R\cdot\sin(\alpha)$. Plate thickness is $d=L\cdot\cos(\alpha)-R\cdot\sin(\alpha)$.

The cone is filled with air and from the plate to the screen is also air with refractive index $n_a=1$. The screen is located at the distance z_e. Plane lightwave, with wavelength λ, incident on the bottom surface of the planparalel plate.

Point P is marked on the screen, to which light wave is reaching, after passing throught cone. One possible traveling direction of the light wave through the slit and to the screen is shown with dotted lines. The direction of propagation of waves does not change when passing through the border surfaces of cone within the plate, which was accepted by [11,12]. After passing the plate, the wavefront travels the distance R_p to the point P on the screen.

It is necessary to examine which part of the path, the light wave propagates through the cone, the plate and from plate to the point P. Considering that plane light wave incident on the lower plain of plate, in a positive direction of z the axis, it is necessary to determine the domain of that wave. The domain of the wave is determined by cone projection on the $z=z_d$ plane. If $\alpha=0$, the projection of the cone on the bottom plane of plate is a circle of radius R, centered on the z axis and the slit is symmetric with respect to the z axis as shown in [11].

If $\alpha>0$, as shown in Fig. 1, the plane of projection of the cone on the plane $z=z_d$ is the surface in the form of the deformed ellipse with the stretched side in the positive direction of the y axis. That surface is not symmetric with respect to the z axis. Because of that it is impossible to solve integral in Eq. (1) analytically and it is necessary to use numerical methods. Details of numerical methods were described in following part of work.

3. Numerical simulation

The projections of the cones on the plane $x=0$ (upper parts of picture) and plane $z=z_d$ (lower parts of picture) are shown on Fig. 2. The dimensions of cones are $R=1$ µm and $L=3$ µm, while rotating angles are $\alpha=0°$, $\alpha=20°$ and $\alpha=40°$. It can be seen from Fig. 2 that projections of cone on surface $z=z_d$ is more deformed with larger angle α. Besides that, thickness of effective layer, d, is decreasing with angle α. It means that with changing of angle α, the domain of wavefront is changing and its optical path to the screen.

Considering that according to of Eq. (1) analytical value of electric field cannot be found at any spot on the screen, it is necessary to do following. Domain (surface) of plain wave at $z=z_d$ is divided in surface segments dS. Electic field at point P on the screen, from segment dS, according to Eq. (1) should be:

$$dE_P=-\frac{i}{\lambda}\frac{1}{r}E\,e^{-i\delta}ds \tag{2}$$

where δ is total phase shift of the light from the segment dS on plane $z=z_d$ to the point P on the screen. Total electric field in point P, from all surface segments on domain of wavefront D (D is the projection of the cone on plane $z=z_d$) can be obtained by summing fields of all surface segments of domain D. Intensity of light in point P on the screen is:

$$I_P=\left|\sum_D dE_p\right|^2 \tag{3}$$

Numerical methodology for determination of the intensity distribution of light on the screen can be described in several steps.

Step 1. Assign the parameters of the cone (R, L), the angle of the cone, α, the distance from the screen plate z_e and light wavelength,