Investigation of collinear acousto-optical diffraction of light fluxes

V N Pichugin, A V Lukishin, O A Pakhomova, O A Dubrovina and E V Yagin
Chuvash state university is named after Ilya Nikolayevich Ulyanov, 15, Moskovsky prospect, Cheboksary, 428015, Russia

E-mail: vladimir_iii@mail.ru

Abstract. A system of differential equations describing collinear light diffraction on a three-dimensional acoustic Zug of finite length with a sinc-shaped time envelope, where linear frequency modulation is used, is obtained. The obtained solutions of differential equations allow us to describe the longitudinal and transverse distribution of the amplitudes of transmitted and diffracted light under strong acoustic-optical interaction. The dependence of the acousto-optical cell bandwidth on the ratio of the Zug length to the crystal, and the filter transmission during light diffraction on acoustic zugs with a sinc-shaped time envelope is studied. The result of this study can be formulated as the development of analytical and software methods for analyzing diffraction pattern of electromagnetic waves in multi-wave mode of reception on infinitely extended object in free space, as well as a software method for calculating diffraction characteristics at frequencies exceeding the basic frequency, taking into account the inhomogeneity of electromagnetic fields in these conditions. The practical significance is the research results used in the development of a universal technique for design and development of radar systems capable of working adequately in conditions of electromagnetic environment in question. The results of this research will allow a more complete description of the electrodynamic picture of wave propagation and its diffraction, namely, taking into account the diffraction properties of radar systems will allow us to develop a direction for their wider production and distribution.

1. Introduction

In multi-location study of the earth's surface, a quantitative description of the phenomena caused by repeated structure and taking into account the influence of the underlying surface properties on the characteristics of the received signals are of great importance [1]. An analysis of characteristics of scattering electromagnetic waves by an ideally conducted ribbon screen located on flat boundary of the conducting dielectric half-space allows us to study problems associated with sharp change in electro physical properties of the earth's surface and the presence of well-reflecting objects located on it [1].

Solutions are known that allow obtaining different estimates of the scattering characteristics of light waves for perfectly conducting disks and bands. However, these solutions are not applicable for radiometric research, since the parameters of the thermal radiation of the medium are determined by active losses in the medium, i.e. the possibility of radiometric observation of objects is due to the difference in their absorption capacity. In a number of papers, the problem of diffraction on an infinitely extended tape in free space is considered. In [2], the problem is reduced to a system of paired integral equations with respect to spectral functions for surface current densities solved by the method of moments. Similar problems for both the impedance tape and the gap in the impedance screen can also be solved by the method of eigenfunctions [3].
Currently, when creating acousto-optical (AO) devices, either glass or crystals are almost always used. Crystals initially have anisotropy of both acoustic and optical properties. Therefore, when an arbitrarily polarized radiation passes through the AO crystal, the light wave splits into two orthogonally polarized components that independently diffract in the acoustic field [4].

Acoustic-optical interaction is a type of diffraction where incident and diffracted light differ only in the direction of polarization and frequency. This type of interaction can be observed exclusively in anisotropic media and in crystals, where there are directions in which both acoustic and light energy propagates without drift. Collinear propagation makes it possible to obtain very large lengths of light-sound interaction when creating experimental acoustic-optical devices, in particular, acoustic-optical filters.

It is known that the bandwidth of acoustic-optical filters is determined by the length of the area of interaction between light and sound, i.e. the length of the acoustic-optical cell and it is inversely proportional to the length of the interaction. Changing the bandwidth of a collinear acoustic-optical filter is possible by controlling an acoustic Zug of finite length, although there are other ways. It is possible to change the characteristics of a collinear filter by changing the duration of the Zug, its shape, or using a linear frequency modulated acoustic signal.

There are several works on light diffraction on acoustic zugs [1, 5], the authors considered the transverse acoustic-optical interaction. In [6], collinear diffraction of light on an acoustic Zug with a Gaussian amplitude distribution taking into account linear frequency modulation and a sinc-shaped time envelope without taking into account linear frequency modulation was studied.

In this paper, we conduct a theoretical study of collinear light diffraction on a three-dimensional acoustic Zug of finite length having a sinc-shaped time envelope with linear frequency modulation [2].

2. Materials and methods
One of the effective methods of study is to solve the problem of diffraction of electromagnetic waves on an infinitely extended object in free space. The purpose of this study is characteristics of electromagnetic waves during diffraction of electromagnetic waves at objects that can be used as radar systems.

A number of works are devoted to theoretical calculation and constructive research of diffraction, in which it is assumed to use non-standard analytical methods of analysis, namely, solving high-order integral and differential equations by changing the coordinate system, solving the boundary problem by dividing a variable based on the expansion of a plane electromagnetic wave into series according to the Mathieu function, Bessel and Hankel functions [3].

The most modern developments are presented by the authors I. Y. Immoreyev, A. G. Loshilov, in patents and research by E. V. Semenov and V. P. Likhachev. Using the ability of some objects not only to scatter the radio waves incident on them, but also to transform their spectrum, allows us to consider a wide range of problems that cannot be solved using traditional methods or are unproductive.

When using nonlinear systems in multi-wave mode, due to the unavailability of reliable calculation tools, it is usually not possible to do without a time-consuming experiment. Based on analytical formulas in a number of sources, you can learn how to develop programs in the integrated environments LabVIEW and MatLab Simulink for numerical calculation of the diffracted field distribution in order to control characteristics.

The LabVIEW research automation package and the MatLab Simulink environment for dynamic interdisciplinary modeling of complex technical systems are offered as modeling tools [3].

3. Interaction with sinc-shaped tsunamis
The diffraction of light on an acoustic Zug is described by the wave equation:

\[
\text{rotrot} \mathbf{E} + \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \left( \delta_{\theta} \mathbf{E} + \Delta \mathbf{A} \mathbf{E} \right) = 0
\]
By $E$ - the strength of the electric field of the light wave, where $c$ - speed of light, $\hat{\varepsilon}_0$ - permittivity tensor of the medium, $\Delta \hat{\varepsilon}$ - change $\hat{\varepsilon}_0$ when exposed to sound, $A$ - acoustic Zug.

The propagation of an acoustic Zug causes elastic deformation of the medium [7], changing the refractive indices of the medium associated with the elastic-optical effect. Therefore, a change in the tensor of the dielectric permeability. The relationship between elastic deformation and changes in the permittivity is as follows:

$$\Delta \varepsilon_{ik} = -N_i^2 N_k^2 \sum_{l,m=1}^{1} p_{klm} S_{lm}$$

(2)

where $N_i, N_k$ - main refractive indices of the medium; $i, k, l, m$ - coordinate indexes; $p_{klm}$ - photoelasticity tensor, $S_{lm}$ - deformation of the crystal.

With linear frequency modulation $\text{sinc}$ - in a figurative acoustic Zug, the frequency and wave vector can be represented as $\Omega = \Omega_0 + \gamma(t - t_0)$, $K = K_0 + \delta(x - x_0)$; $\Omega_0$, $K_0$ - central frequency and wave vector of the acoustic Zug; $\gamma$, $\delta$ - coefficients that characterize the degree of change in the frequency and wavelength of the Zug; $t_0, x_0$ - initial time and coordinate of the interaction of light and sound in the cell.

Using the spectral representation of transmitted and diffracted light, the acoustic Zug:

$$U_{\omega}(k_x, k_y, x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{\omega}(x, y, z) \exp[-j(k_x y + k_y z)] dy dz$$

$$C(K_x, K_y, x, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A(x, y, z, t) \exp[-j(K_x y + K_y z)] dy dz$$

(3)

We obtain a system of differential equations describing collinear light diffraction:

$$\frac{df_\omega(x)}{dx} = -jQ_1 f_\omega(x) \frac{\exp[-j\eta(\xi + \delta(vt - x))]}{1 - jDx + r_0^2 I R} \text{sinc}\left(\frac{vt - x}{l}\right)$$

$$\frac{df_\omega(x)}{dx} = -jQ_2 f_\omega(x) \frac{\exp[j\eta(\xi + \delta(vt - x))]}{1 + jDx + r_0^2 I R} \text{sinc}\left(\frac{vt - x}{l}\right)$$

(4)

with initial conditions $f_\omega(-L/2) = 0$, $f_\omega(-L/2) = 1$.

System equations (4) there is something other than the equations of coupled waves. The physical meaning is that they determine the relationship between the amplitudes of incident and diffracted waves as they propagate in a perturbed medium [8].

4. Conclusion

Since the sound Zug has finite dimensions, the diffraction efficiency can be determined not by the ratio of the power densities of the incident and diffracted light, but by the ratio of the power fluxes in the diffracted and incident light beams. In a light beam the power flux is calculated as the square of the light field distribution modulus over the beam cross section:

$$P = \frac{1}{2} \int_s |E_\omega| ds$$

(5)

To analyze the efficiency of acousto-optical diffraction (5), we pass to dimensionless quantities and make approximations, then the solution of the system of differential equations is realized by recurrent relations:
\[
\begin{align*}
    f_d^{(r+1)} &= f_d^{(r)} + hF_1(\xi, f_t^{(r)}) \\
    f_t^{(r+1)} &= f_t^{(r)} + hF_2(\xi, f_d^{(r)})
\end{align*}
\]

with initial conditions \( f_t^{(0)} = 1, f_d^{(0)} = 0 \), where \( h = 1/N, \) step, \( N \) number of segments. Various numerical and asymptotic methods can be used to solve the obtained systems of equations [9].

Figure 1. Transmission curve of the filter at different points in time for a short train with a sinc-shaped.

A software tool in the Matlab Simulink integrated environment has been developed for the numerical solution, which allows you to get on the screen the filter transmission Curves at various points in time for a short Zug with a sinc-shaped shape, by analyzing the diffraction light characteristics (see figure 1).

Software tool that implement the built virtual models are developed in the MatLab Simulink and LabVIEW research automation package [10].

The developed software technique can be used to analyze the effects of diffraction of light streams in the design of radar problems.

The main result of the study can be formulated as the development of software methods for analyzing the effects of diffraction of light fluxes, as well as a software method for calculating diffraction characteristics at frequencies higher than the fundamental frequency, taking into account heterogeneity in these conditions.

Within the main research area, the following specific tasks were solved:

1. a mathematical model of light diffraction has been Developed;
2. as a result of the analysis, formulas for calculating the diffraction dependences are obtained, which give a satisfactory agreement with the experimental data;
3. a software simulator has been Developed to study the effects of light diffraction.

During research, algorithm was developed for asymptotic or numerical simulation of diffraction pattern of electromagnetic waves in multi-wave mode of reception on an infinitely extended object in free space, as well as a software method for calculating diffraction characteristics at frequencies exceeding the fundamental frequency, taking into account inhomogeneity of electromagnetic fields in these conditions [4]. The developed methodology for researching characteristics of electromagnetic waves during diffraction of electromagnetic waves at objects can be used in design and development of radar systems capable of working adequately in the conditions of electromagnetic environment under consideration. Based on the provisions and conclusions, a software tool was developed. The results of the study can become the basis for development of means of electromagnetic compatibility of radar objects. Based on the recommendations developed in this study, new methods can be developed to improve the efficiency of radar systems.
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