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A rigorous theoretical model of guided waves excitation in a plane dielectric layer under electromagnetic diffraction by a conducting strip

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ABSTRACT

An exact solution of two-dimensional problem of plane electromagnetic wave scattering by a perfectly conducting strip in the presence of a parallel plane dielectric layer is presented. The given solution is constructed using the mode-matching technique in the form of diffraction integrals over propagation parameter, i.e. in the form of superposition of a large number of homogeneous and inhomogeneous plane waves with continuous spectrum of spatial frequencies. These integrals have poles, which are caused by the presence of a transparent dielectric layer and correspond to its waveguide modes. Because of this, diffraction integrals need the procedure of regularization with explicit extraction of pole terms and smoothing of integrands, whereupon the residual diffraction integrals are computed using simple numerical methods. They describe usual scattered field of a bounded obstacle, which is determined by regularized diffraction integrals and decreases in all directions from an obstacle. Besides, the total diffraction field contains a discrete finite sum of waveguide fields of guided modes of a plane dielectric layer, which correspond to the extracted pole terms of initial diffraction integrals. These fields correspond to pairs of guided waves, which move apart from the region of their excitation near a strip, propagating parallel to the boundaries of a layer and conserving finite amplitude at infinity.

1. Introduction

The phenomenon of guided waves excitation in plane dielectric layered structures is of great importance for modern quantum electronics, optical communication, optoelectronics and microwave integrated electronics [1–5]. The nature of this phenomenon consist in conversion of the external incident electromagnetic radiation into waveguide modes, which propagate along the boundaries of a guiding structure and decay outside that in lateral direction, i.e. undergo total internal reflection on these boundaries [1–9]. Tangential spatial frequencies corresponding to such behavior of waveguide modes, are absent usually in external incident field, because it does not decay in the exterior space and propagates under the harmonic law. It is clear, that excitation of guided field in a plane guiding dielectric structure can be realized only under conversion of incident radiation into the field, containing plane-wave components, which correspond to waveguide modes and undergo total internal reflection on the boundaries of a waveguide. In other words, one should realize a space-to-guide couple. For such conversion, various methods are used [3–9]. The most simple of those is suitable choice of propagation geometry, when an external field contains required spatial components initially, i.e. when this field propagates parallel to the boundaries of a waveguide and falls on its butt-end [6]. However, usually cross section of waveguide structures is rather small in comparison with the cross section of an incident beam, so this method is effective only for planar radiation sources [7], but for volume ones it is characterized by very small value of conversion efficiency. The prism conversion method is more effective [6,7]. Here, one uses a prism with inclined sides for energy conversion from incident radiation into waveguide modes. But for integrated optics and optoelectronics this method is not always acceptable owing to large dimensions of a prism. Up to now, the diffraction conversion methods are widely practiced [6–9]. They utilize various diffraction elements, mostly diffraction gratings. Such elements have small dimensions, allowing planar performance on common base with a dielectric waveguide, and are characterized by rather high efficiency of conversion of incident radiation into guided field.

The purpose of a diffraction element is broadening of tangential spatial frequencies spectrum of incident radiation up to appearance in that the waves with propagation parameters of waveguide modes. For the case of grating coupling elements, their parameters are selected so as to provide coincidence of tangential propagation parameters of nonzero diffraction orders with propagation parameters of a waveguide mode [6–9]. Apart from diffraction elements with discrete spectrum of plane waves, as a grating, one can use also such ones, which scatter initial incident radiation in the form of very wide continuous spatial spectrum, containing

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certainly the spatial frequencies of waveguide modes of located nearby a guiding dielectric structure. As an example of an element with rather wide scattering spectrum, one can consider a point or linear scatterer, which can be represented by the sharp edge of a conducting surface [10]. And two such edges of a perfectly conducting strip, placed near a dielectric waveguide, create the most simple finite diffraction element with wide scattering spectrum. In this work, we study such a type of diffraction structure with parallel orientation of a strip and a plane transparent dielectric layer.

On practical plane, the field of applications of the diffraction method of waveguide excitation is impressive enough, but the theory here falls behind the experiment. As it is known for us, rigorous methods were not used for theoretical description of the diffraction processes of providing guided radiation inside plane dielectric waveguides. Only approximate methods have been used for theoretical modeling, such as the method of Kirchhoff's integral and the method of Green's function [8,11–23]. In itself, the last method is rather rigorous, but in application to the problems of waveguide excitation it yields a solution in the form of intricate integrals, which usually are computed asymptotically. Exactly, attempts to apply the rigorous Wiener–Hopf method to waveguide problems run into serious difficulties with determination of factorized functions, which have been calculated approximately [24]. The main difference between waveguide problems and usual problems of the rigorous diffraction theory is the presence of an infinite or semi-infinite layered dielectric structure under excitation. But in the presence of such structures, the integral expressions, describing diffraction fields, have poles, whose location corresponds to parameters of waveguide modes propagation inside dielectric structures [8,17]. Such poles are typical for scattering matrix, which is used in the quantum scattering theory [25]. There, they describe bound states of a quantum system, which are characterized by finite motion in space and correspond to one of discrete values of its energy. As we can see, there is obvious analogy with diffraction excitation of guiding structures in electrodynamics: waveguide modes are also determined by discrete set, but not of energy and of parameter of propagation, and their region of existence actually is bounded in space, because the fields of these modes decay exponentially out of a guiding system. However, in the electromagnetic diffraction theory, a correct computation technique for integrals with poles is not elaborated for simulation the process of excitation of waveguide fields in plane guiding structures. In the given work, we suggest an exact method of computation of diffraction integrals with waveguide poles in application to the problem of plane electromagnetic wave diffraction by a strip and a parallel infinite plane dielectric layer.

2. General solution for plane wave diffraction by a strip and a parallel dielectric layer

Let us consider the two-dimensional problem of plane electromagnetic wave diffraction by a conducting strip and a plane dielectric layer (Fig. 1). As it is known [26,27], such problems

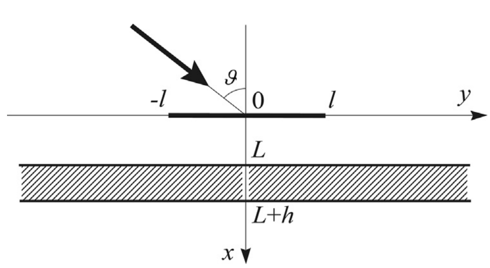

Fig. 1. Wave diffraction by a conducting strip and a parallel dielectric layer.

allow for field separation into two independent polarizations *H* and *E*, or *TE* and *TM*, as they are denoted more often in optics, the first of which is defined by orthogonality of the electric vector to the plane of wave propagation (xOy), and the second one is characterized by perpendicularity of the magnetic vector to this plane.

H polarization (*TE*)

$$E_z = u \quad H_x = -\frac{i}{k}\frac{\partial u}{\partial y} \quad H_y = \frac{i}{k}\frac{\partial u}{\partial x} \tag{1a}$$

E polarization (*TM*)

$$E_x = \frac{i}{k}\frac{\partial u}{\partial y} \quad E_y = -\frac{i}{k}\frac{\partial u}{\partial x} \quad H_z = \varepsilon(x)u \tag{1b}$$

where u is the complex scalar function, different for various polarizations, which satisfy the Helmholtz's equations [26,27] (we use the C.G.S. system of units)

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + k^2\varepsilon(x)u = 0 \tag{2}$$

Here, $k = \omega/c$ is the wave number, $i = \sqrt{-1}$ is the imaginary unite, $\varepsilon(x)$ is the piecewise constant function, which equals to the permittivity ε of a dielectric inside that or unity outside the layer. It is supposed that temporal dependence of fields is determined by the exponential factor $\exp(-i\omega t)$, which is omitted everywhere.

Let the plane wave

$$u = \exp[\,ik(\alpha_0 x + \beta_0 y)] \tag{3}$$

is incident from negative x and y on the infinitely thin perfectly conducting strip $-l \le y \le l$, located in the plane $x = 0$ (Fig. 1), where ${\alpha_0}^2 + {\beta_0}^2 = 1$. It is assumed that for the *H* and *E* polarizations, the expression (3) determines the E_z and E_y components of an incident wave, respectively.

We shall construct a solution of our diffraction problem on the basis of the method, which was used for solving simpler problem of wave diffraction by an isolated strip in absence of a dielectric layer [28]. According to this method, we can seek diffraction fields as a superposition of large number of plane waves, which propagate away from the plane $x = 0$, containing an obstacle. To take into account the presence of a plane dielectric layer, one should allow for reflection and refraction on its boundaries for every plane wave of diffraction spectrum by means of introducing amplitude multiplies, proportional to the corresponding coefficients of reflection and refraction [27,29]. Proceeding from these considerations, let us seek the diffraction fields in the following form with explicit separation of the incident and reflected plane waves:

before the layer ($x \le 0$)

$$u(x,y) = \alpha_0^{-\nu}(e^{ik\alpha_0 x} + R_{\text{ala}}^{(0)} e^{ik\alpha_0(2L-x)})e^{ik\beta_0 y} \pm \int_{-\infty}^{+\infty} A(\beta)\,(1 \pm R_{\text{ala}}(\beta)\,e^{2ik\alpha L})e^{ik(-\alpha x+\beta y)}\alpha^{-\nu}d\beta \tag{4}$$

between a strip and a dielectric layer ($0 \le x \le L$)

$$u(x,y) = \alpha_0^{-\nu}(e^{ik\alpha_0 x} + R_{\text{ala}}^{(0)} e^{ik\alpha_0(2L-x)})e^{ik\beta_0 y} + \int_{-\infty}^{+\infty} A(\beta)\,(e^{ik\alpha x} + R_{\text{ala}}(\beta)\,e^{ik\alpha(2L-x)})e^{ik\beta y}\alpha^{-\nu}d\beta \tag{5}$$

in a dielectric layer ($L \le x \le L+h$)

$$u(x,y) = \frac{T_{\text{al}}^{(0)}}{\alpha_0^{\nu}D^{(0)}}(e^{ik\gamma_0(x-L)} - R_{\text{al}}^{(0)} e^{ik\gamma_0(2h+L-x)})e^{ik(\alpha_0 L+\beta_0 y)} + \int_{-\infty}^{+\infty} A(\beta)\,\frac{T_{\text{al}}(\beta)}{\alpha^{\nu}D(\beta)}(e^{ik\gamma(x-L)} - R_{\text{al}}(\beta)\,e^{ik\gamma(2h+L-x)})e^{ik(\alpha L+\beta y)}d\beta \tag{6}$$