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Diffraction of electromagnetic waves by a metallic bar grating with a defect in dielectric filling of the slits

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ABSTRACT

The problem of electromagnetic wave diffraction by the metallic bar grating with inhomogeneous dielectric filling of each slit between bars has been investigated by using the mode matching technique. The transmission and the inner field distribution have been analyzed for the structure which has a single defect in the periodic filling of slits. Such periodic structures are of particular interest for applications in optics, as they have the ability to concentrate a strong inner electromagnetic field and are characterized by high-Q transmission resonances. We use a simple approach to control the width and location of the stopband of the structure by placing a defect in the periodic filling of the grating slits. As a result, we observe the narrow resonance of transmission in terms of stopband width of the defect-free grating and confinement of strong inner electromagnetic field. By changing the permittivity of the defect layer we can shift the frequency of the resonant transmission.

1. Introduction

Diffraction of electromagnetic waves by periodic structures has attracted much attention since the early twentieth century [1–3]. Periodic structures have frequency-response characteristics with alternating passband and stopband, and are widely used in different electronic, quantum optics and optical devices [4,5]. For example, the periodic multi layered structures are used to create a new class of very bright light-emitting diodes which were shown both theoretically and experimentally in [6–10]. Control of the stopband and passband of the structure can be performed by changing the characteristics of one or several unit cells of the periodic system, which breaks the periodicity of the structure. The structures with such defect in their periodicity can be used to design narrow-band filters [11]. The defect can be imbedded into the one dimensional periodic multilayer structure by inserting an extra layer with different thickness or refractive index [12]. In order to keep the geometrical parameters of the periodic system a layer can be replaced by a defect layer made of different materials [13–15]. In this case there is a defect in a periodic structure, because the permittivity of the defect element differs from the permittivity of the original ones.

In this paper we investigate diffraction properties of a periodic grating, which consists of perfectly electric conducting (PEC) bars. There is multilayered dielectric filling in the slits between the bars. In the slit, each dielectric layer is characterized by its own value of the permittivity. The difference of the studied grating in compare to the multilayered structures with defect [16,17] is that we consider a multilayer dielectric filling with a defect in the grating slits. The point of such grating is the magnitude of the electric field localized in the defect of the grating is much higher than the electric field magnitude in the defect of all-dielectric multilayer structures. The intensity of the electric field plays an important role in the manifestation of nonlinear effects, for example, when the defect layer of the grating is formed from a nonlinear dielectric [18,19]. Thus, our theoretical study of the frequency characteristics of the grating and the estimation of the electric field in the defect shows that the metal bar grating is promising for further investigations with a nonlinear dielectric defect in the filling of the slits. In our research we are following the method of the solutions of the problem of diffraction by PEC bar grating with homogeneous filling of the slits, which is considered in [20,21]. In contrast, we have investigated the case of the grating with inhomogeneous filling of slits. In this work we consider the slits, which are filled periodically by two types of dielectric layers. The defect is located in the place of the middle layer in each slit. The defect layer has the same thickness as all layers however its permittivity is different. The first work on the study of this structure was mentioned by us in [22], but there were a number of

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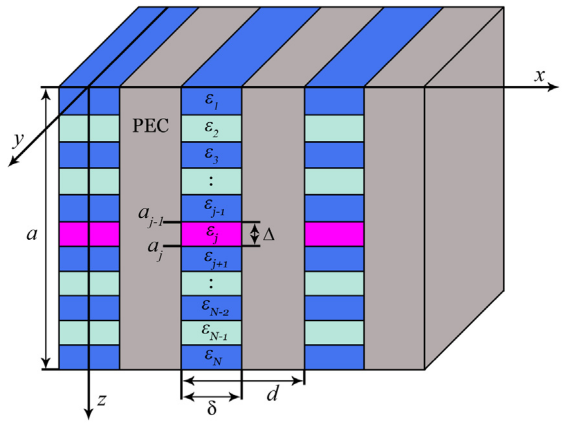

Fig. 1. PEC bar grating with a single defect in dielectric filling of the slits. Three periods of an infinitely periodic structure are presented. The defect layer is located between the boundaries a_{j-1} and a_j.

layers in the slits $N = 11$ and less detailed analysis of the structure characteristics was presented. Thus multilayered filling of each slit is an analog of a one-dimensional photonic crystal with a defect which has a finite cross size the same as the width of the slits [23–25].

The goal of this paper is to study the frequency-selective properties of the PEC bar grating with regular and defect fillings of the slits. We make a comparative analysis of the frequency-selective characteristics of both the defect grating and the regular grating. We show that the increasing and decreasing the value of the defect permittivity drastically affects an inner electromagnetic field in the structure. In fact, the defect grating shows the transmittance in terms of the frequency stopband of the PEC bar gratings without defect and confines the strong inner electromagnetic field.

2. Statement and solution of the problem

We study a diffraction of the normal incident of a plane electromagnetic wave linearly polarized in the x-direction by the periodic grating of the PEC bars with rectangular cross section (Fig. 1). We assume the amplitude of the incident field is 1 a. u. The width of the slit between bars is δ. The slits are filled by a periodic set of dielectric layers of the same thickness Δ. We assume that the grating pitch d is comparable to or smaller than the wavelength of incident wave. The case of TE polarization is less important than the case of TM polarization, because the electric field cannot penetrate into the narrow slit. We are interested in high-Q resonances with a high field density distribution, which appear only in the case of TM polarization.

The electromagnetic field scattered by the grating we represent by sets of plane waves in both $z < 0$ and $z > a$ regions. The electromagnetic fields inside the slits of the grating are represented by a set of waves of planar waveguide. For the regions above, below and inside the grating, the expressions for only one component of the magnetic field are

$$H_y(x,z) = \begin{cases} \exp(ikz) + \sum_{n=-\infty}^{\infty} a_n \exp\left(-\tilde{\tau}_n z\right)\exp(i2\pi nx/d), & z<0; \\ \sum_{m=0}^{\infty}\left(c_m^j \exp\left(\tilde{q}_m^j\left[z-\Delta(j-1)\right]\right) + d_m^j \exp\left(-\tilde{q}_m^j\left[z-\Delta j\right]\right)\right)\cos\left(\pi m\left(x/\delta+0.5\right)\right), & a_{j-1}<z<a_j \\ \sum_{n=-\infty}^{\infty} b_n \exp\left(\tilde{\tau}_n (z-a)\right)\exp(i2\pi nx/d), & z>a, \end{cases} \tag{1}$$

where a_n and b_n are amplitudes of space harmonics of the reflected and transmitted fields correspondingly, c_m^j and d_m^j are amplitudes of mth waveguide modes propagating along the z-axis (in forward and backward direction correspondingly) in the jth layer of the slit filling, $k = 2\pi/\lambda$, $\tilde{\tau}_n = ik\sqrt{1-(\lambda n/d)^2}$, $\tilde{q}_m^j = ik\sqrt{\varepsilon_j - (\lambda m/2\delta)^2}$, $j = 1,\ldots,N$.

The problem is solved by the mode matching technique described in detail in [26]. The electric field is determined using expression (1) and Maxwell's equations. The boundary conditions are imposed at the plane $z = 0$

$$1 - \sum_{n=-\infty}^{\infty} a_n \tau_n \exp(i2\pi nx/d) = 0, \qquad \delta/2 < |x| < d/2; \tag{2}$$

$$1 - \sum_{n=-\infty}^{\infty} a_n \tau_n \exp(i2\pi nx/d) = \frac{1}{\varepsilon_1}\sum_{m=0}^{\infty}\left(c_m^1 - d_m^1 \exp\left(i2\pi q_m^1 \kappa r\right)\right) q_m^1 \cos\left(\pi m(x/\delta+0.5)\right), \qquad |x| < \delta/2; \tag{3}$$

$$1 + \sum_{n=-\infty}^{\infty} a_n \exp(i2\pi nx/d) = \sum_{m=0}^{\infty}\left(c_m^1 + d_m^1 \exp\left(i2\pi q_m^1 \kappa r\right)\right)\cos\left(\pi m(x/\delta+0.5)\right) \qquad |x| < \delta/2, \tag{4}$$

and the plane $z = a$

$$\sum_{n=-\infty}^{\infty} b_n \tau_n \exp(i2\pi nx/d) = 0, \qquad \delta/2 < |x| < d/2; \tag{5}$$

$$\sum_{n=-\infty}^{\infty} b_n \tau_n \exp(i2\pi nx/d) = \frac{1}{\varepsilon_N}\sum_{m=0}^{\infty}\left(c_m^N \exp\left(i2\pi q_m^N \kappa r\right) - d_m^N\right) q_m^N \times \cos\left(\pi m(x/\delta+0.5)\right), \qquad |x| < \delta/2; \tag{6}$$

$$\sum_{n=-\infty}^{\infty} b_n \exp(i2\pi nx/d) = \sum_{m=0}^{\infty}\left(c_m^N \exp\left(i2\pi q_m^N \kappa r\right) + d_m^N\right) \times \cos\left(\pi m(x/\delta+0.5)\right), \qquad |x| < \delta/2, \tag{7}$$

where $\tau_n = \sqrt{1-(n/\kappa)^2}$, $q_m^j = \sqrt{\varepsilon_j - (m/2\kappa\theta)^2}$, $\kappa = d/\lambda$ is normalized frequency, $\theta = \delta/d, h = a/d, r = \Delta/d$. Hereafter the normalized frequency is referred to as the frequency.

The amplitudes of space harmonics of the scattered field a_n and b_n are found by scalar multiplication of expressions (2) and (3) and (5) and (6) by the basis functions $\exp(i2\pi s(x/d))$, respectively

$$a_s = \delta_{s0}/\tau_s - \left(0.5\theta/\varepsilon_1\tau_s\right)\sum_{l=0}^{\infty}\left(c_l^1 - d_l^1 \exp\left(i2\pi q_l^1 \kappa r\right)\right) q_l^1 w_{sl}^*, \tag{8}$$

$$b_s = \left(0.5\theta/\varepsilon_N\tau_s\right)\sum_{l=0}^{\infty}\left(c_l^N \exp\left(i2\pi q_l^N \kappa r\right) - d_l^N\right) q_l^N w_{sl}^*, \tag{9}$$

where $w_{sl} = \exp(0.5i\pi l)\sin c(\pi(\theta s+0.5l)) + \exp(-0.5i\pi l)\sin c(\pi(\theta s-0.5l))$, w_{sl}^* is the complex conjugate of w_{sl}, $\delta_{l0} = \begin{cases}1, l=0\\ 0, l\neq 0\end{cases}$ is Kronecker symbol, $\sin c(x) = \sin(x)/x$.

In order to derive the set of linear algebraic equations for calculating the amplitudes of waveguide modes in the first layer c_m^1, d_m^1 and in the last layer c_m^N, d_m^N, we used the functional Eqs. (4), (7) and the completeness of the set of basis functions $\cos(\pi l(x/\delta+0.5))$. Thus, c_m^1, d_m^1 and c_m^N, d_m^N are found by scalar multiplication of expressions (4) and (7) on the basis function, respectively

$$c_l^1 + d_l^1 \exp\left(i2\pi q_l^1 \kappa r\right) = \delta_{l0} + 1/\left(1+\delta_{l0}\right)\sum_{s=-\infty}^{\infty} a_s w_{sl}, \tag{10}$$

$$c_l^N \exp\left(i2\pi q_l^N \kappa r\right) + d_l^N = 1/\left(1+\delta_{l0}\right)\sum_{s=-\infty}^{\infty} b_s w_{sl}. \tag{11}$$

We derive the set of equations for amplitudes of waveguide modes by substituting expressions (8) and (9) in right parts of (10), (11). This system of equations is transformed to the system of linear algebraic equations for amplitudes of waveguide modes in the first layer of dielectric filling of the slit by using a transfer matrix. For instance, right-to-left transfer matrix derives the relation of amplitudes of waveguide