INFLUENCE OF HARD CORRUGATED PBG WALL DESIGN ON PERFORMANCE OF CONICAL HORN ANTENNA

Sergei Skobelev1 and Per-Simon Kildal2
1 JSC “Radiophyzika” Moscow 123363, Russia
2 Department of Electromagnetics Chalmers University of Technology S-412 96 Gothenburg, Sweden

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ABSTRACT: Some numerical results for a conical horn with three modifications of a hard corrugated PBG wall are presented. It is shown that a completely corrugated horn of diameter 4–5 wavelengths provides 80–87% aperture efficiency and a cross-polar level below −30 dB for a horn length greater than 20 wavelengths. © 2002 John Wiley & Sons, Inc. Microwave Opt Technol Lett 32: 265–268, 2002.

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1. INTRODUCTION

Periodic structures have always been one of the important subjects for investigation and application in the optic and microwave areas. During the past years, starting from [1] and [2], the interest in periodic structures has been stimulated by the work in optics on so-called photonic bandgap (PBG) materials and photonic crystals (PCs). Then, studies were quickly extended to the microwave area, and even to acoustics, where the acronyms PBG and PC are used as before, although the associations with the term “photonic” in the indicated areas is completely misleading. Moreover, some properties of the PBG structures, e.g., high surface impedance, and some of their applications, like those associated with reducing the coupling between elements, make them similar to the periodic structures classified as soft and hard surfaces [3, 4]. And vice versa, the hard corrugated surfaces are actually anisotropic PBG structures. To correct the situation, journals and some authors introduced the terms “electromagnetic structures” and “electromagnetic bandgap materials” [5–7], although most authors continue using the term “photonic bandgap,” and in particular, the acronym PBG. Since it seems already strongly established in the microwave and antenna areas, we will also use this acronym below, but we will replace the term “photonic” by the much more appropriate term “periodic.”

One of the promising applications of the PBG structures is the enhancement of the aperture efficiency and the reduction of the cross-polar level in horn antennas. This is of interest, in particular, for improvement of the performance of cluster feeds [8], and for providing a uniform excitation of quasioptical amplifier arrays [9, 10]. Examples of structures by which the indicated characteristics can be obtained are hard corrugated PBG walls [11] and hard strip-loaded walls [12]. Although the latter is characterized by high surface impedance, it supports undesirable surface waves, which destroy the performance. However, they can be removed by vias [13], and then the hard strip-loaded wall can be attributed to the class of PBG structures. An attempt to apply a new uniplanar compact PBG structure for obtaining a uniform field distribution in a rectangular waveguide has been presented in [14].

Some important results on hard corrugated and strip-loaded conical horns reported in [11, 15], and [16] have been obtained by using a circular cylindrical waveguide model for calculation of the operating modified TE11-mode characteristics with subsequent calculation of the radiation characteristics by the Kirchhoff–Huygens method, taking into account only the undisturbed field of the incident mode. This approach has allowed drawing some important conclusions on the potentials of the hard horns; however, the predicted cross-polar level below −30 dB has not been achieved in the experimental samples [15]. This fact is obviously explained by the distortions that occur both when the operating mode passes through the horn and when it is scattering at the horn end. The account for the indicated effects, as noted in [8], requires using a more rigorous approach. In the present letter, we present some numerical results obtained when studying the influence of the hard corrugated PBG wall design on performance of a conical horn antenna. The analysis has been carried out on the basis of the generalized scattering matrix method, which makes it possible to take into account all of the effects mentioned above.

2. HORN DESIGN AND METHOD OF ANALYSIS

The geometry of the horn to be studied is presented in Figure 1. It is assumed that the metallic conical horn of length L and aperture diameter 2b is fed in the operating TE11 mode from a regular circular waveguide of diameter 2a0. The inner surface of the horn is partly [Fig. 1(a)] or completely [Fig. 1(b, c)] loaded with metallic longitudinal corrugations whose grooves are filled with a dielectric of relative permittivity ε. The groove depth changes from zero at the beginning (to diminish the discontinuity of the junction) to t = b − a at the aperture, where a is the radius of the central part of the

Figure 1 Three modifications of hard corrugated PBG wall design in conical horn antenna
latter. To minimize the cross-polar level, the value of $t$ is usually chosen a little smaller than that corresponding to the hard wall boundary condition

$$J_0(ka')Y_1(kb') - Y_0(ka')J_1(kb') = 0$$

derived by using the asymptotic boundary conditions for corrugated surfaces [17], where $J_n(\ldots)$ and $Y_n(\ldots)$ are Bessel and Neumann functions of the $n$th order, respectively, $a' = (s - 1)/2a$, $b' = (s - 1)/2b$, $k = 2\pi/\lambda$, and $\lambda$ is the operating wavelength.

We consider three modifications of the PBG wall design in the horn. In the first modification [Fig. 1(a)], the inner corrugated surface is cylindrical. This modification is the most preferable from the viewpoint of the mechanical horn design because the corrugations occupy a relatively small part of the horn. Such a design has been considered in [18] without using the dielectric filling of the grooves, and in [19] for a description of the hard horns. In the second modification [Fig. 1(b)], the inner corrugated surface is a conical one which starts to coincide with the beginning of the basic horn surface. The corrugated surface in the third modification [Fig. 1(c)] consists of two parts. The first part is a continuation of the cylindrical surface of the input guide, while the second part is a conical surface whose vertex coincides with the vertex of the basic horn surface.

The analysis of the horn has been carried out using a model where the conical surfaces have been replaced by stepped surfaces formed by a set of cylindrical sections with appropriate flanges. The generalized scattering matrices for the steps have been calculated by the mode-matching method, and the necessary eigenmodes of the corrugated sections have been determined using the asymptotic boundary conditions [17]. The scattering matrix of the stepped transition between the input guide and the last section has been calculated as a result of a multiple solution of the problem about two series waveguide discontinuities, as, for instance, described in [20]. This conventional part of the algorithm has been supplemented with an accurate account of the wave scattering at the open end of the corrugated waveguide. The structure at the open end has been considered as two infinitely close discontinuities, the first of which is a junction of the corrugated and empty waveguides, and the second of which is the open end of the empty guide. The scattering matrix for the first discontinuity has been determined by the method of factorization [21]. As demonstrated in [22], the indicated approach has allowed considerable refinement of the results obtained by the Kirchhoff–Huygens method. The characteristics of the open-ended corrugated waveguide and the scattering matrix of the transition then have been used for calculation of the horn characteristics as a whole, including its VSWR, aperture efficiency, and maximum cross-polar level.

3. RESULTS OF CALCULATIONS

The operation of the computer code developed according to the algorithm described above has been tested in a few known ways. The energy balance both for each step and for the transition as a whole is satisfied up to the sixth decimal digit. The convergence test has shown that the results for $b \leq 3\lambda$ are stabilized at a number of steps of about $100 \times (b - a_0)/\lambda$ with account for 20–30 modes of each direction at each side of a step. Finally, the numerical results for a special case corresponding to the first horn modification [Fig. 1(a)] without filling the grooved with dielectric are in good agreement with the experimental data available in [18].

As an illustrative example, we consider a horn with aperture parameters $b = 2\lambda$, $a = 1.775\lambda$, and $\varepsilon = 2$. The calculations show that the corresponding semi-infinite open-ended waveguide, which can be treated as a limiting case of the horn without the quadratic phase distribution of the aperture field and without the interaction between the aperture and throat, is characterized by an aperture efficiency of 88.5% and a maximum cross-polar level of $-40.5$ dB. The indicated characteristics as functions of the horn length $L$ with $a_0 = 0.4\lambda$ are shown in Figure 2. The general feature of the presented curves is oscillations caused by the interaction between the horn throat and aperture over the higher order modes, while the VSWR of the horn deviates around the value of 1.05. The aperture efficiency rises with an increase of the horn length, and this behavior corresponds to a reduction of the phase errors in the aperture field distribution. The increase of the horn length results in a reduction of the cross-polarization level as well.

Comparison of the characteristics corresponding to the three modifications of the wall design shows that the simplest design [Fig. 1(a)] provides the worst performance. Two more complex modifications with a completely corrugated wall increase the aperture efficiency by a few percent (about 5% in the presented example), and reduce the cross-polar level by more than 10 dB. These features that are revealed as a result of the calculations can be explained as follows. In the first modification, the conical TE$_{11}$ mode formed at the throat proceeds without distortions only up to the beginning of the corrugated section. Then, it is split into TE and TM modes.

![Figure 2](image-url)
propagating in the corrugated section independently of each other (in the frame corresponding to the asymptotic boundary conditions [17, 18]). As a result, the operating modified TE_{11} mode, which should have a uniform field distribution in the central region at the end of the corrugated section, comes to the aperture a priori with considerable distortions, and additional distortions arise when the modes scatter at the open end. In the third modification [Fig. 1(c)], the modified conical TE_{11} mode formed at the throat comes to the aperture without any distortions, and the distortions arise only as a result of its scattering at the open end. The second horn modification [Fig. 1(b)] is close to the third one, and for this reason, the worsening of the horn performance in comparison to the third modification is not considerable.

An example demonstrating the changing of the horn performance for the third wall modification while changing the permittivity of the dielectric in the grooves and while changing the aperture diameter is shown in Figure 3. If, in the horn considered above, we use a dielectric with $\varepsilon = 1.5$, the optimum groove depth at the aperture corresponds to $a = 1.71\lambda$. The open-ended corrugated waveguide with the indicated parameters has an aperture efficiency of 83.3% and a maximum cross-polar level of $-38.1\, \text{dB}$. A comparison of the curves, corresponding to changing the horn characteristics with a change of the horn length, with similar curves in Figure 2, shows that the dielectric with smaller permittivity provides a better cross-polar performance; however, this is at the expense of some reduction of the aperture efficiency. For greater aperture radius $b = 2.5\lambda$ and the same $\varepsilon = 1.5$, the optimum radius of the central region is $a = 2.19\lambda$. The open-ended waveguide with these parameters gives an aperture efficiency of 85.7% and a maximum cross-polar level of $-41.1\, \text{dB}$. Thus, the use of a dielectric with greater permittivity and an increase of the horn aperture require a corresponding increase of the horn length for achieving a higher aperture efficiency while keeping a low cross-polar level.

4. CONCLUSION

In this letter, we have presented some numerical results obtained for a conical horn antenna with three modifications of the wall design on the basis of a hard corrugated periodic bandgap (PBG) structure. The calculations have been carried out by using the method of generalized scattering matrices and the method of factorization, which allow revealing all of the effects associated with the propagation of the operating mode through the horn and with wave scattering at the open end. The results show that the simplest wall design with a cylindrical surface of corrugations occupying only a part of the horn provides the worst performance. However, if the corrugations occupy all of the inner horn surface, and especially if the basic and corrugated conical surfaces have the same vertex, then the horn aperture efficiency rises by a few percent, and the cross-polar level is reduced by more than $10\, \text{dB}$. It is also shown that the completely corrugated hard horn with an aperture diameter of 4–5 wavelengths and a permittivity of the wall filling of 1.5–2 can provide an aperture efficiency of 80–87% and a cross-polar level below $-30\, \text{dB}$ when its length is greater than 20 wavelengths.

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ELECTROMAGNETIC SCATTERING FROM NONUNIFORM MAGNETIZED FERRITE CYLINDER

B. J. Hu,¹ E. K.-N. Yung,¹ and X. Q. Sheng¹
¹Department of Electronic Engineering
City University of Hong Kong
Kowloon, Hong Kong SAR, P. R. China

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ABSTRACT: An analytical technique, called the scattering matrix method, is developed to analyze the scattering of a plane wave from a nonuniform ferrite cylinder. It is proved that the derived formulas for nonuniform ferrite cylinders can be degenerated to the formulas for uniform ferrite cylinders published in the literature. The characteristics of scattering by ferrite cylinders with a linear profile are investigated versus applied magnetic fields and wave frequencies.

II. FORMULATION

Consider the scattering of a TM wave normally incident to a nonuniform ferrite cylinder shown in Figure 1, where the nonuniform ferrite cylinder is divided into p layers. A magnetic bias field $H_0$ is applied along the $z$-direction; thus, the permeability tensor in the $m$th layer is $[\mu^{(m)}]$:

$$[\mu^{(m)}] = \begin{bmatrix} \mu_1^{(m)} & j \mu_2^{(m)} & 0 \\ -j \mu_2^{(m)} & \mu_3^{(m)} & 0 \\ 0 & 0 & \mu_0 \end{bmatrix}$$

with

$$\mu_1^{(m)} = \mu_0 \left( 1 + \frac{\omega_0^{(m)^2} (\omega_0^{(m)} + j \omega_0^{(m)})}{(\omega_0^{(m)} + j \omega_0^{(m)})^2 - \omega^2} \right)$$

$$\mu_2^{(m)} = \mu_0 \frac{\omega_0^{(m)} (\omega_0^{(m)} + j \omega_0^{(m)})^2 - \omega^2}{(\omega_0^{(m)} + j \omega_0^{(m)})^2}$$

where $\omega_0^{(m)} = \gamma \mu_0 H_0^{(m)}$ is the precession frequency, $\omega_0 = \gamma \mu_0 M_0^{(m)}$, and $\omega$, $\gamma$, $M_0^{(m)}$, $\alpha^{(m)}$, and $\mu_0$ are the wave frequency, the gyromagnetic ratio, the saturation magnetization, the damping factor, and the permeability in free space, respectively. It is known that the electric field of the incident TM wave can be written in the following form:

$$E_i^z = E_0 e^{-j k_0 \rho \cos \varphi}$$

which can be expanded in terms of the Bessel function $J_n$ as

$$E_i^z = E_0 \sum_{n=-\infty}^{+\infty} (-j)^n J_n(k_0 \rho) e^{-jn \varphi}$$

where $E_0$ is the amplitude and $k_0$ is the wavenumber in free space. The scattered electric field in free space can be written as

$$E_s^z = E_0 \sum_{n=-\infty}^{+\infty} A_n (-j)^n H_n^{(2)}(k_0 \rho) e^{-jn \varphi}$$

where $A_n$ are coefficients to be determined and $H_n^{(2)}$ are the Hankel functions of the second kind. Thus, the total field in the incident region is obtained:

$$E_z = E_i^z + E_s^z = E_0 \sum_{n=-\infty}^{+\infty} (-j)^n [J_n(k_0 \rho) + A_n H_n^{(2)}(k_0 \rho)] e^{-jn \varphi}.$$  \(7\)

In the $m$th ferrite layer, the total electric field can be written as [15]

$$E_z^{(m)} = E_0 \sum_{n=-\infty}^{+\infty} (-j)^n \times [B_n^{(m)} J_n(k_0 \rho) + C_n^{(m)} H_n^{(2)}(k_0 \rho)] e^{-jn \varphi}$$  \(8\)