Modal Spectrum of Planar Dielectric Waveguides With Quasi-Periodic Side Walls

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***Abstract*—This work presents an in-depth theoretical analysis of a planar layered dielectric waveguide with periodic side walls. It is shown that, apart from the conventional guided modes for which most of their energy travels within the dielectric dense medium, this guide presents other modes whose energy mostly travels in the air regions inside the side walls or outside them. In particular, the mode with its energy traveling inside the side walls is a low-loss and weakly dispersive mode that could be of interest for practical applications. Moreover, it has been demonstrated that this mode can be strongly excited by a realistic source, which has been done by showing that this mode is the main part of the spectrum radiated by a dipole line located within the air region inside the side walls.**

***Index Terms*—Periodic structures, planar dielectric waveguides.**

I. Introduction

As is well known, guidance of high-frequency electromagnetic waves in dielectric waveguides is possible thanks to the total internal reflection at the interface between two different dielectric media (optical fibers and integrated planar dielectric guides are examples of this class of waveguides). The electromagnetic field of the modes guided by this type of structures is strongly confined within the dense medium, which always exhibits some level of material losses. Moreover, these guided modes are typically strongly dispersive (i.e., their effective dielectric constant shows a strong dependence with frequency) and present important angle limitation with respect to bending the guiding channel. With the aim of overcoming the abovementioned drawbacks inherent to total internal reflection, it would be very convenient to develop dielectric waveguides whose electromagnetic-guided field mainly travels within a lossless air region bounded by dielectric walls. This type of mode is expected to exhibit low levels of losses and dispersion, thus, making it a perfect candidate for low-loss and low-dispersion transmission of very-high-frequency electromagnetic waves (submillimeter, infrared and optical bands, for instance). In recent years, an all-dielectric coaxial waveguide that resembles the behavior of the transverse electromagnetic (TEM) mode guided by the ordinary coaxial cable made of copper has been proposed [1]. This proposal is based on the omnidirectional reflection properties of a layered periodic dielectric structure [2]. The almost-perfect (but lossy) metallic mirror in the case of the copper coaxial cable is substituted by a perfect dielectric mirror provided by a periodic dielectric configuration (for a certain frequency range). The result is an all-dielectric guiding structure that is not based on the phenomenon of total internal reflection. The guidance property of a dielectric fiber of this type was experimentally demonstrated in [3].

In order to give proper credit to previous research on this topic, it is worth mentioning that, to the authors' knowledge, the physics background underlying these findings was discussed three decades ago by Larsen and Oliner [4] in the frame of the microwaves community. In that work, the authors proposed essentially the same idea as in [1] to achieve a low loss waveguide. The main difference was the planar geometry of the structure considered in [4] versus the cylindrical geometry of the structure proposed in [1]. In the present contribution, we will recall the planar structure to carry out an in-depth analysis of the different types of guided modes supported by a planar waveguide whose walls are made with a periodic dielectric of finite size. The eigenvalue problem is solved by making use of a very efficient method to deal with layered planar configurations recently proposed in [5]. It is demonstrated that conventional modes with the energy confined within the high-dielectric-constant materials (in-dielectric modes) exist together with certain bound modes having most of the energy confined in the air region (out-dielectric modes), either in the interior between the periodic dielectric walls or in the exterior around them. Moreover, making use of a method similar to that recently reported in [6], the practical excitation of the bound out-dielectric modes by a normal-to-interfaces electric dipole line is studied. It is shown that the main part of the spectrum of the electromagnetic field excited by this idealized source is composed of an interior out-dielectric mode. This fact opens the possibility of using this mode to transmit high-frequency electromagnetic fields with a planar layered structure with very low losses and dispersion.

II. Periodic Dielectric Walls

In this section, the guiding structure shown in Fig. 1, which consists of an air region of thickness d limited by two symmetric dielectric layered configurations having a dielectric constant periodic along the y-direction (the repeated unit cell is a pair of layers with permittivities ε_1 and ε_2 and thicknesses d_1 and d_2), will be studied.

Although, in practice, the number of layers must be limited, a first study of the infinite periodic structure along the y-direction

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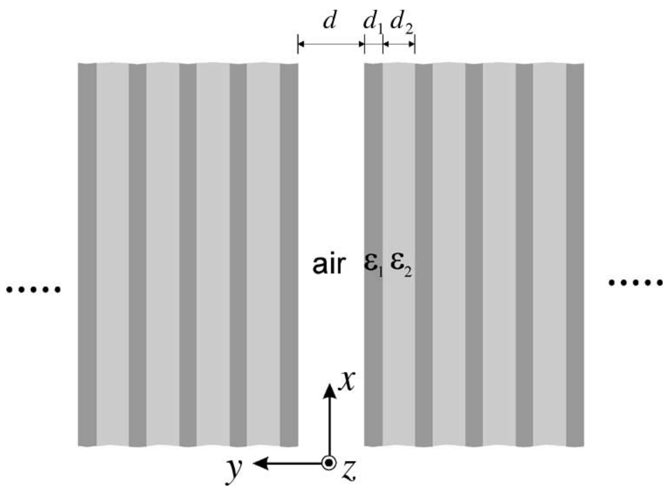

Fig. 1. Planar waveguide consisting of an air region of thickness d bounded by two periodic dielectric layered configurations. The unit cell is built up by two dielectric layers characterized by permittivities $\varepsilon 1$ and ε_2 and thicknesses d_1 and d_2.

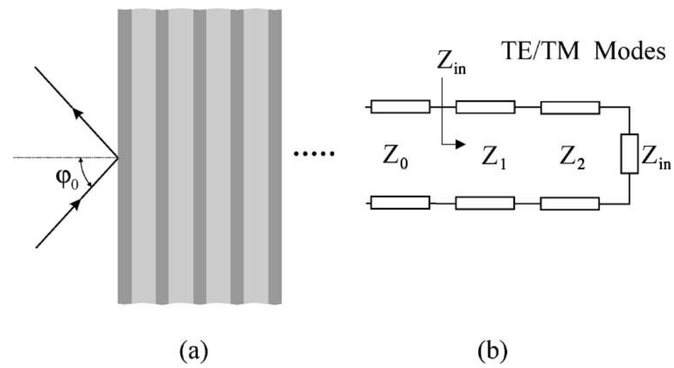

Fig. 2. (a) Original and (b) equivalent transmission line for TE/TM modes.

can help in obtaining a physical insight on the phenomenon considered here. Specifically, this study will show that, for appropriate values of the electrical and dimensional parameters, the layered periodic configurations behave as perfect mirrors within a certain frequency band for a planar electromagnetic wave incident on the structure from an arbitrary direction. This phenomenon will be observed when the input impedance Z_{in} at the $y = 0$ plane of the periodic layered structure becomes purely imaginary for any incidence angle, so that the periodic walls behave as reactive loads reflecting all the electromagnetic power incident from any angle.

The input impedance can be computed using the equivalent transmission line structure for transverse electric (TE) and transverse magnetic (TM) modes [see Fig. 2(b)] of the reflection problem in Fig. 2(a). In this way, the input impedance as a function of the incidence angle φ_0 is found to be the solution of a quadratic equation given by

$$Z_{\text{in}} = Z_2 \frac{Z + \text{j}Z_2 \tan\theta_2}{Z_2 + \text{j}Z \tan\theta_2} \tag{1}$$

$$Z = Z_1 \frac{Z_{\text{in}} + \text{j}Z_1 \tan\theta_1}{Z_1 + \text{j}Z_{\text{in}} \tan\theta_1} \tag{2}$$

where

$$\theta_i = \beta_i d_i \cos(\varphi_i), \qquad i = 1, 2$$

$$\sin(\varphi_i) = \sqrt{\frac{\varepsilon_0}{\varepsilon_i}} \sin(\varphi_0)$$

$$\beta_i = \omega\sqrt{\mu_0 \varepsilon_i}$$

$$Z_i = \begin{cases} \sqrt{\frac{\mu_0}{\varepsilon_i}} \sec(\varphi_i), & \text{for TM modes} \\ \sqrt{\mu_0 \varepsilon_i} \cos(\varphi_i), & \text{for TE modes.} \end{cases}$$

In particular, the combination of (1) and (2) leads to an equation for Z_{in}, written as

$$\begin{aligned} &(Z_1 \tan\theta_2 + Z_2 \tan\theta_1) Z_{\text{in}}^2 \\ &\quad + \text{j}\left(Z_1^2 - Z_2^2\right) \tan\theta_1 \tan\theta_2 Z_{\text{in}} \\ &\quad - Z_1 Z_2 (Z_1 \tan\theta_1 + Z_2 \tan\theta_2) = 0 \end{aligned} \tag{3}$$

which allows us to finally compute the reflection coefficient as

$$\Gamma(\omega) = \frac{Z_{\text{in}}(\omega) - Z_0}{Z_{\text{in}}(\omega) + Z_0} \tag{4}$$

with $Z_0 = (\mu_0/\varepsilon_0)^{1/2}$.

The analysis above applied to the structure considered in Fig. 3 shows that there exists a wide frequency range where the magnitude of this coefficient is unity. (Similar plots can be found for different parameters of the two dielectric layers unit cell). The existence of this frequency band suggests that guided modes with a high degree of confinement in air (outside the dielectrics) are expected to be found when the walls of the structure in Fig. 1 are fabricated with a number of cells with the same characteristics as those used to generate Fig. 3. This significant fact will be verified in the next section.

III. Modal Spectrum of the Planar All-Dielectric Parallel Plate Guide

The electromagnetic propagation in a realistic guiding structure (with a finite number of layers) derived from Fig. 1 will now be considered as an eigenvalue problem. This problem is solved by means of the method proposed in [5], which allows us to obtain all the modes of a layered structure in a very efficient and systematic way. Thus, Fig. 4 shows the dispersion relation of all the above-cutoff even modes (even with respect to E_y) of the modal spectrum corresponding to a planar waveguide whose periodic side walls have been modeled by nine-layer configurations with the same structural parameters as those previously employed for Fig. 3.

It can be observed in this figure that, in addition to dispersion relations typical of dielectric waveguide modes whose electromagnetic field mainly travels through a dense medium (modes $\text{TE}_1 - \text{TE}_5$ and $\text{TM}_0 - \text{TM}_3$), there appear a couple of modes (TM_4 and TM_5) whose normalized propagation constants are close to unity for frequencies ranging from 27 to 36 GHz.

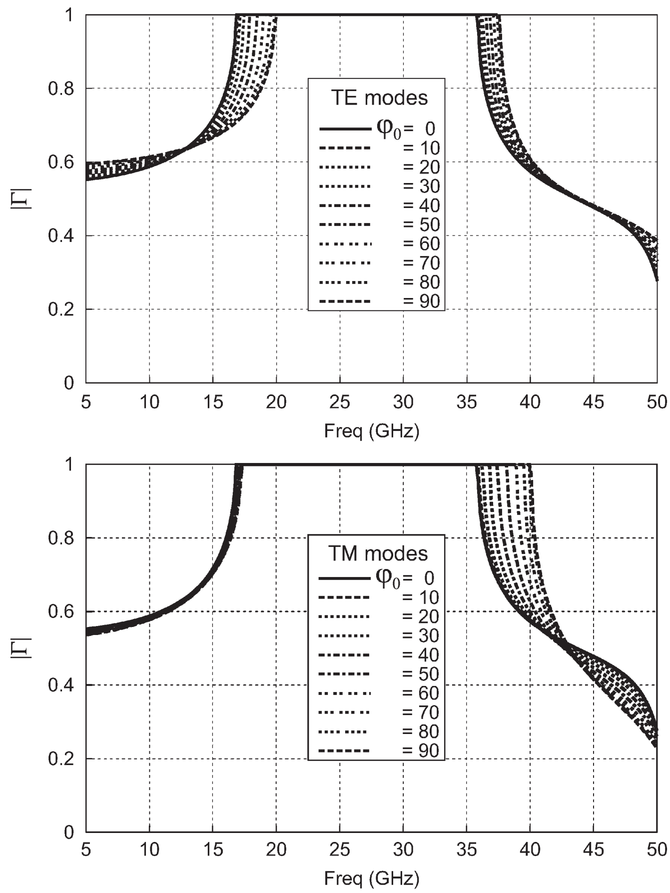

Fig. 3. Magnitude of the TE/TM reflection coefficient $|\Gamma|$ for a waveguide as in Fig. 2 with $\varepsilon_1 = 36\varepsilon_0$, $\varepsilon_2 = 3.2\varepsilon_0$, $d_1 = 500\ \mu$m, and $d_2 = 1500\ \mu$m.

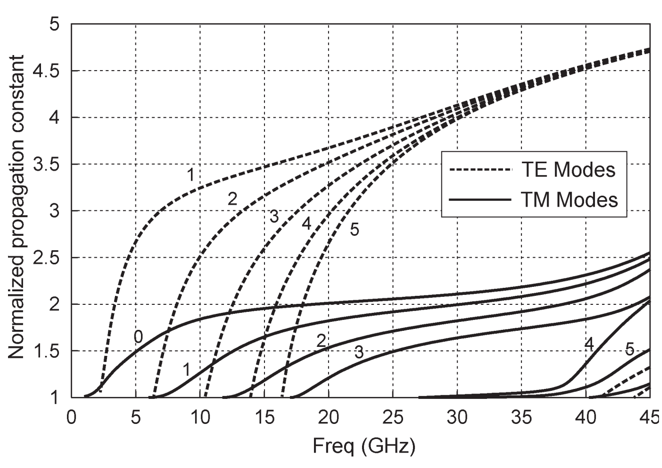

Fig. 4. Dispersion relation for the even modes (with respect to E_y) of a waveguide with an air region of thickness $d = 4$ mm (see Fig. 1) bounded by two symmetric layered configurations of nine layers, each one having four two-layer unit cells with $\varepsilon_1 = 36\varepsilon_0$, $\varepsilon_2 = 3.2\varepsilon_0$, $d_1 = 500\ \mu$m, and $d_2 = 1500\ \mu$m, and one additional layer with $\varepsilon_1 = 36\varepsilon_0$ and $d_1 = 500\ \mu$m. The propagation constants are normalized to $k_0 = \omega(\varepsilon_0\mu_0)^{1/2}$.

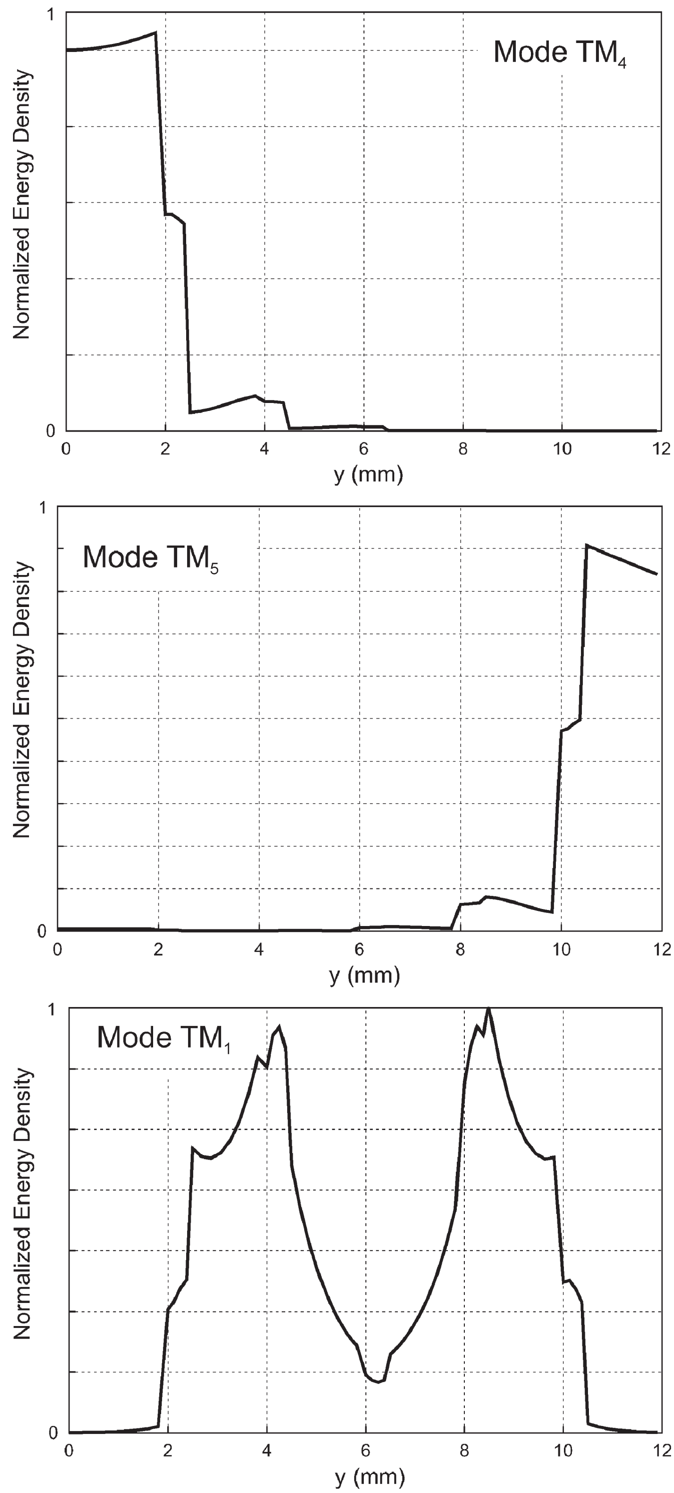

Fig. 5. Distribution of the electromagnetic energy density at 30 GHz corresponding to the two out-dielectric modes (TM_4 and TM_5) and one "in-dielectric mode" (TM_1) for the waveguide analyzed in Fig. 4.

For these latter modes, and within the abovementioned frequency range, the layered side walls seem to behave as perfect mirrors, which could be an indication that these modes are the desired low-dispersion and low-loss modes. In order to study the differences in the field distribution for the so-called "out-dielectric modes" (TM_4 and TM_5) and the remaining "in-dielectric modes," the energy densities for the two out-dielectric modes and one of the in-dielectric modes are plotted in Fig. 5 at 30 GHz. The in-dielectric mode (TM_1) clearly presents an electromagnetic field distribution that is strongly concentrated within the dielectric layers $(2.0 < y\ (\mathrm{mm}) < 10.5)$. A low percentage of the total energy travels in the air regions inside and outside the periodic layers. Total internal reflection must

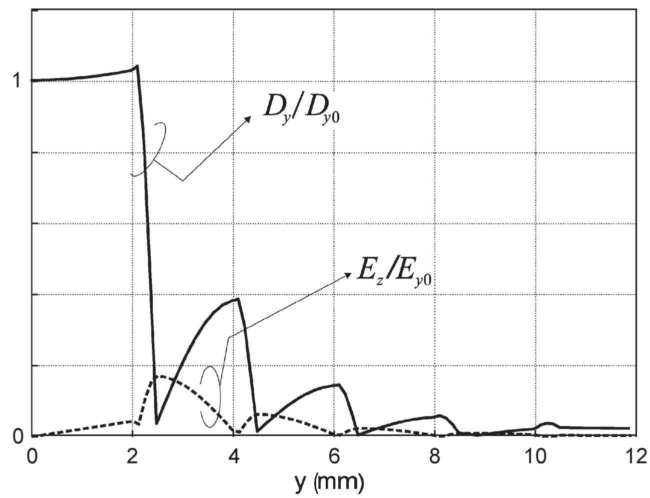

Fig. 6. Solid line: profile of the normalized magnitude of the normal component of the displacement field $D_y(y)/D_{y0}$ for the TM_4 mode previously analyzed in Fig. 5 $[D_{y0} = D_y(0)]$. Dashed line: ratio between the magnitudes of the tangential electric field $E_z(y)$ and the value of the normal electric field at $y = 0$.

be invoked to explain this type of field confinement. On the contrary, the energy distribution of the out-dielectric modes (TM_4 and TM_5) shows that most of its energy propagates in the air regions; although these two modes present very different field distributions. In particular, the TM_5 mode has most of its energy outside the periodic layers in the exterior air regions (and then it will be called exterior out-dielectric mode), whereas the TM_4 mode presents an energy confinement in the interior air region (this mode will then be called interior out-dielectric mode). It can also be appreciated that the energy profile of this latter mode shows a high degree of resemblance with that of a metallic parallel-plate TEM waveguide. This fact can be further inspected, looking at the magnitude of the normal component of the electric displacement field plotted in Fig. 6. Moreover, the dashed line of this figure also shows a longitudinal electric field component much less significant than the transverse one, which confirms that the field configuration of the interior out-dielectric mode is qualitatively like the constant y-directed field found for the TEM mode of a parallel-plate transmission line. Therefore, and provided that this mode can be excited effectively, a situation where a quasi-TEM mode propagates in an all-dielectric planar structure has been found. It can be very useful to guide electromagnetic energy at very high frequencies, since the abovementioned mode is hardly dispersive (its phase constant β is approximately equal to k_0 within a relatively wide frequency band) and would present a low level of losses (its energy travels mostly in the air region).

IV. Excitation of the Interior Out-Dielectric Mode

Although our previous study of the propagation problem has revealed the existence of a TM mode confined to the interior air region of the structure under consideration, it should be noted that the presence of such mode in the modal spectrum of the transmission system does not necessarily mean that this mode can be strongly excited in a practical situation. Thus, in order to properly establish the physical significance of the interior out-dielectric mode, this section will study the "degree of excitation" of this mode when a source feeds the waveguide. This task will be carried out by considering an infinite-length waveguide (along the longitudinal z-direction) excited by a time-harmonic dipole line placed on the interior air region of the waveguide. (An analogous procedure was already used, for example, in [6] and [7] with similar purposes to study other excitation problems.) Since the interior out-dielectric mode has a TM nature, the dipole line will be oriented normal to the interfaces to excite only TM modes; that is, the impressed current density will be assumed to be

$$\mathbf{J}(\mathbf{r}, t) = \delta(x)\delta(y - y')\mathrm{e}^{\mathrm{j}\omega t}\hat{\mathbf{y}}. \tag{5}$$

The above-mentioned source could also roughly simulate the realistic excitation of the waveguide by means of a y-polarized electric field impinging on the interior air region of the waveguide.

Because of the translational symmetry of the structure, the normal electric field can be computed by means of an inverse Fourier transform, which is written as

$$E_y(x, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G_{yy}^{EJ}(k_x; y, y')\mathrm{e}^{-\mathrm{j}k_x x} dk_x \tag{6}$$

where $G_{yy}^{EJ}(k_x; y, y')$ is the yy component of the spectral Green's dyadic at y due to a source located at y', and k_x is the spectral variable associated with x. No integration is performed with respect to the longitudinal Fourier variable k_z because of the invariance of the source along the longitudinal direction.

In general, $G_{yy}^{EJ}(k_x, k_z; y, y')$ can be readily obtained from the dual of the tangential spectral Green's dyadic, $\overline{\mathbf{G}}_t^{EJ,D}(k_x, k_z; y, y')$, as explained in the Appendix. Thus, the normal electric field can finally be computed, for the excitation given in (5), as

$$E_y(x; y, y') = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{k_x^2 \widetilde{G}_{zz}^{EJ,D}(k_x; y, y'|k_z = 0)}{k_0^2 - k_x^2} \mathrm{e}^{-\mathrm{j}k_x} dk_x. \tag{7}$$

For a practical and efficient numerical computation of the abovementioned integral, it should be considered that the integrand presents branch points at $k_x = \pm k_0$ and poles on the real axis in the interval $k_0 \leq k_x < (\max(\varepsilon_r))^{1/2} k_0$ [10]. This drawback can be readily overcome by taking an integration contour partially running on the third and first quadrants of the complex k_x plane [6], [7], [10].

When the abovementioned procedure is applied to the structure previously analyzed in Fig. 4 at a frequency of 30 GHz, the computed $E_y(x)$ field is plotted in Fig. 7. This field distribution shows a rather complex profile because of the multimodal TM nature of the field at this frequency (six TM even modes are above cutoff at 30 GHz, which results in the various peaks observed in Fig. 7 because of the multiple constructive and destructive interferences between the different modes).

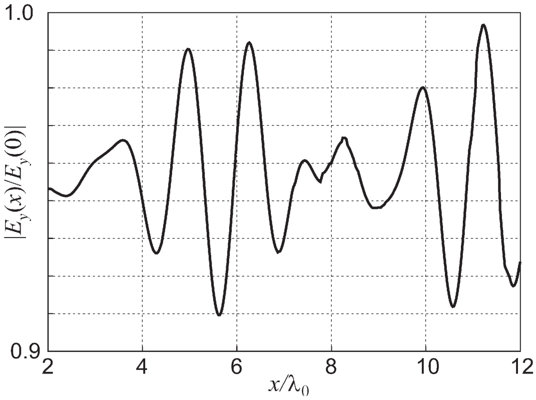

Fig. 7. Normalized magnitude of the normal electric field with respect to the transverse direction for the structure previously analyzed in Fig. 4; $y = 0.7$ mm; $y' = 1.4$ mm; Freq $= 30$ GHz.

Once the normal electric field has been computed, the study of its corresponding modal spectrum will reveal which modes actually compose this spectrum, as well as their degree of excitation. This study has been performed by applying the generalized pencil of functions (GPoF) [11] to obtain the decomposition of $E_y(x)$ as an expansion of exponentials terms. Specifically, the GPoF gives the N-term approximation for $E_y(x)$, which is written as

$$E_y(x) \approx \sum_{n=1}^{N} A_i \mathrm{e}^{-\mathrm{j}\gamma_i x}. \tag{8}$$

(The number of terms N can be internally determined by the GPoF depending on the required accuracy [11].) Each term of the above-mentioned expansion will then account for one component of the modal spectrum; the amplitude A_i and the exponent γ_i of the different terms can be identified with the modal amplitude (and, therefore, its corresponding degree of excitation) and the modal propagation constant of the associated modes.

The application of the GPoF analysis to the $E_y(x)$ field plotted in Fig. 7 gives the results shown in Table I, which have been computed using 400 sample points in the $2 < x/\lambda_0 < 12$ range and with the GPoF accuracy parameter set to -3 [11]. Table I also shows the normalized phase constant (β/k_0) of the even TM modes previously computed in the two-dimensional (2-D) eigenvalue analysis. It can be observed that an excellent agreement is found between the exponents provided by the GPoF and the modal propagation constants. Specifically, the expansion given by the GPoF has four exponential terms, whose predominant term (that with maximum amplitude A_1) corresponds to the TM_4 interior out-dielectric mode. The remaining three exponential terms have much lower excitation amplitudes and can be readily identified with other TM waveguide modes of the structure. Thus, these results clearly show that the field excited in the waveguide by the considered dipole line will be mostly guided in the form of the interior out-dielectric mode. It is also important to mention that the TM_5 exterior out-dielectric mode is not excited at all (as expected) by the source located in the interior air region.

TABLE I
RESULTS FOR THE NORMALIZED PHASE CONSTANTS AND AMPLITUDES OF THE MODAL SPECTRUM FOR THE STRUCTURE OF FIG. 4

Freq=30 GHz		β/k_0	
Waveguide modes	TM_0	2.1081460	
	TM_1	1.9944637	
	TM_2	1.8219144	
	TM_3	1.6387934	
	TM_4	1.0172868	
	TM_5	1.0009554	
		Exponent γ_i/k_0	Amplitude, A_i/A_1
GPoF	$\sim TM_4$	1.01728-j0.76E-05	1.0000
	$\sim TM_3$	1.63748-j0.21E-02	0.0094
	$\sim TM_2$	1.82507-j0.13E-02	0.0091
	$\sim TM_0$	2.00107+j0.95E-02	0.0025

V. CONCLUSION

The present paper has studied the modal spectrum of a waveguide constituted by an air region bounded by two periodic side walls. A simple analysis of the reflection coefficient of the ideal structure shows that the periodic side walls are expected to behave as perfect mirrors within a certain frequency range. A detailed analysis of the dispersion relation of the even TM and TE modes of a realistic structure with nine layers simulating the periodic side wall has revealed the existence of two modes whose normalized phase constant remains close to unity for a frequency range similar to that found for perfect reflection in the ideal structure. A further study of the energy distribution of these two modes has shown that only one of them is confined to the interior air region, thus, suggesting the resemblance of this mode with a mode guided by almost-perfect mirrors at high frequency. The analysis of the polarization of this interesting mode has confirmed its quasi-TEM-like behavior. Finally, an analysis of the degree of excitation of this mode by a realistic source has been carried out. This analysis has evidenced that this mode is expected to be strongly excited by an impinging wave whose electric field is polarized along the vertical direction.

APPENDIX

The computation of $G_{yy}^{EJ}(k_x, k_z; y, y')$ is clearly equivalent to obtaining the y-component of the electric field at y due to the sheet of normally directed current filaments given as

$$\mathbf{J}(\mathbf{r}) = \delta(y - y') \exp(-\mathbf{j}\mathbf{k}_t \cdot \boldsymbol{\rho})\hat{\mathbf{y}} \tag{9}$$

where $\mathbf{k}_t = k_x\hat{\mathbf{x}} + k_z\hat{\mathbf{z}}$ (the subscript t denotes tangential to the interfaces). According to [10], the abovementioned sheet of normally directed electric current is equivalent to the sheet of tangential magnetic current given as

$$\mathbf{M}_t = \frac{1}{\omega\varepsilon_s}\mathbf{k}_t \times \mathbf{J}_y \tag{10}$$

where ε_s is the permittivity of the layer where the source is located.

From Maxwell's equations, the normal electric field $\mathbf{E}_y$ due to (9) within a layer of permittivity ε_f can be computed as

$$\begin{aligned}\mathbf{E}_y &= -\frac{1}{\omega\varepsilon_f}\mathbf{k}_t \times \mathbf{H}_t \\ &= -\frac{1}{\omega\varepsilon_f}\mathbf{k}_t \times \overline{\mathbf{G}}_t^{HM}(k_x, k_z; y, y') \cdot \mathbf{M}_t \end{aligned} \qquad (11)$$

where the tangential magnetic field has been expressed in terms of the tangential Green's dyadic that relates this field with a tangential magnetic current $\overline{\mathbf{G}}_t^{HM}(k_x, k_z; y, y')$. If the tangential magnetic current is related to the sheet of normally directed electric current through (10), (11) can be rewritten as

$$\mathbf{E}_y = -\frac{1}{\omega^2\varepsilon_f\varepsilon_s}\mathbf{k}_t \times \overline{\mathbf{G}}_t^{HM}(k_x, k_z; y, y') \cdot (\mathbf{k}_t \times \mathbf{J}_y) \qquad (12)$$

which finally allows us to write

$$\begin{aligned}&G_{yy}^{EJ}(k_x, k_z; y, y') \\ &\quad = -\frac{1}{\omega^2\varepsilon_f\varepsilon_s}\left\{k_x^2 G_{zz}^{HM} - 2k_x k_z G_{xz}^{HM} + k_z^2 G_{xx}^{HM}\right\}. \end{aligned} \qquad (13)$$

Following the duality principle [10], the dyadic $\overline{\mathbf{G}}_t^{HM}(k_x, k_z; y, y')$ can be readily related to the dual of the tangential electric field–electric current dyadic $\overline{\mathbf{G}}_t^{EJ,D}(k_x, k_z; y, y')$, with the latter being the tangential electric field–electric current dyadic associated with the dual structure. The computation of the dyadic Green's function G_t^{EJ} for layered structures can be carried out, for instance, following the scheme in [8] and [9].

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