Radiation Characteristics of a Dielectric Slab Waveguide Periodically Loaded with Thick Metal Strips

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Abstract —A theoretical analysis is presented for the radiation characteristics of a dielectric slab waveguide periodically loaded with thick metal strips. A boundary-integral-equation formulation is employed to describe the fields in the grating layer. Through numerical calculations, we show that the leakage constant of the fundamental TM mode is much larger than that of the fundamental TE mode. This property will find application in mode filters for millimeter- and submillimeter-wave integrated circuits.

I. Introduction

OPEN PERIODIC dielectric waveguides are of great importance as, for example, grating couplers at optical wavelengths [1] and leaky-wave antennas at millimeter-wave frequencies [2], for coupling dielectric-based integrated circuits and the outer free space.

In optical grating couplers, the periodic variation is made mainly in the form of periodic corrugations of the waveguide surface or periodic permittivity modulations of one of the constituent layers [3]. For millimeter- and submillimeter-wave applications, we can introduce the periodic perturbation by loading a dielectric waveguide with metal strips in addition to the means used at optical wavelengths [4], [5].

Theoretical treatments of such a strip-loaded dielectric waveguide reported have so far been confined to the case where the metal strips are infinitely thin [6]–[8]. In this paper, we present an analysis employing a boundary-integral-equation formulation for the radiation characteristics of a dielectric slab waveguide loaded with thick metal strips. Through numerical calculations, we show that the leakage constant of the fundamental TM mode is much larger than that of the fundamental TE mode. Utilizing this property, we will be able to make a mode filter [9] for millimeter- and submillimeter-wave integrated circuits.

II. Derivation of the Characteristic Equation

The radiation characteristics of open periodic waveguides can be described mainly by the complex propagation constant β_0 of the fundamental space harmonic supported by the structure. In this section, we derive the characteristic equation, from which we can evaluate β_0 numerically by means of a boundary-integral-equation formulation.

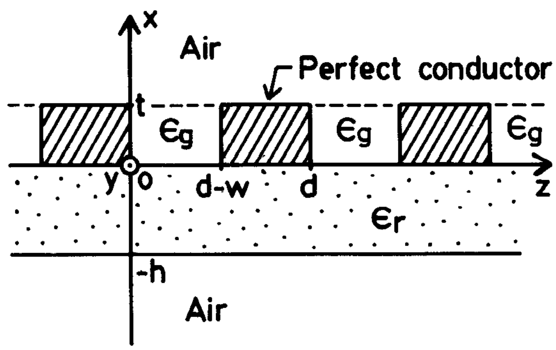

Fig. 1. Periodically strip-loaded dielectric slab waveguide.

Fig. 1 shows the periodic waveguide to be analyzed in this paper. The dielectric slab has thickness h and relative permittivity ϵ_r. With a period d, the slab is loaded with perfectly conducting metal strips which have a rectangular cross section of thickness t and width w. The region between the metal strips is assumed to be filled with a medium of relative permittivity ϵ_g. It is assumed that the fields have no variation in the y direction and that the time dependence of the field is $\exp(j\omega t)$.

A. Boundary Integral Equation

We denote the region $0<x<t$, $0<z<d-w$ in Fig. 1 as R, and the contour enclosing R as L (see Fig. 2). The electromagnetic field ϕ in R satisfies the two-dimensional Helmholtz equation

$$\nabla_t^2\phi + k_0^2\epsilon_g\phi = 0 \tag{1}$$

where

$$\phi = \begin{cases} E_y & \text{for TE polarization} \\ H_y & \text{for TM polarization} \end{cases}$$

$$\nabla_t = \boldsymbol{a}_x\frac{\partial}{\partial x} + \boldsymbol{a}_z\frac{\partial}{\partial z}.$$

Here $\boldsymbol{a}_x$ and $\boldsymbol{a}_z$ are the unit vectors along the x and z directions, respectively, and k_0 is the free-space wavenumber. With the aid of the two-dimensional Green's function,

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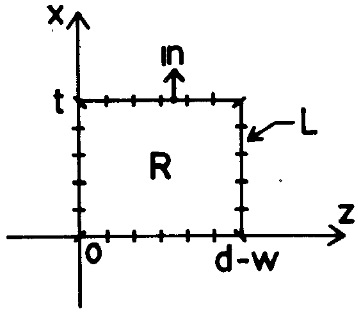

Fig. 2. Region in which the fields are described by a boundary-integral equation.

(1) can be converted to the following boundary-integral equation whose unknowns are ϕ and $\partial\phi/\partial n$ on L [10], [11]:

$$\frac{1}{2}\phi(r_0) = \fint_L \left(\psi \frac{\partial \phi}{\partial n} - \phi \frac{\partial \psi}{\partial n} \right) dl \tag{2}$$

where r_0 is a point on $L, \fint$ denotes the principal value integral with singularities removed, $\partial/\partial n$ is the outward normal derivative on L, and ψ is the Bessel function of the second kind and zeroth order[1]

$$\psi(r, r_0) = -\frac{1}{4} N_0\left(k_0 \epsilon_g^{1/2} |r - r_0|\right).$$

After dividing L into N segments, we expand the unknown functions ϕ and $\partial\phi/\partial n$ in series of step functions S_i, each of which has a constant value of 1 over the ith segment, as follows:

$$\phi = \sum_{i=1}^{N} u_i S_i(r) \tag{3a}$$

$$\frac{\partial \phi}{\partial n} = \sum_{i=1}^{N} q_i S_i(r). \tag{3b}$$

Substituting (3a) and (3b) into (2), and locating the point r_0 on the midpoint of each segment, we obtain a matrix equation of the form

$$(G)(u) + (H)(q) = 0 \tag{4}$$

where G and H are square matrices of order N, and u and q are unknown column vectors with elements u_i and q_i ($i = 1 \sim N$), respectively.

B. Boundary Condition at $x = t$

According to Floquet's theorem, we express the field ϕ in the upper half space $x > t$ by

$$\phi = \sum_{n=-\infty}^{\infty} a_n e^{-jk_{xn}^{(a)}(x-t)} e^{-j\beta_n z} \tag{5}$$

[1]The Hankel function of the second kind and zeroth order $H_0^{(2)}$ is usually employed as the Green's function when the two-dimensional Helmholtz differential equation is converted to a boundary-integral equation.

In this paper, since we describe the field by an integral equation in the region inside a closed contour, we can use the Bessel function of the second kind N_0 instead of $H_0^{(2)}$ as the Green's function.

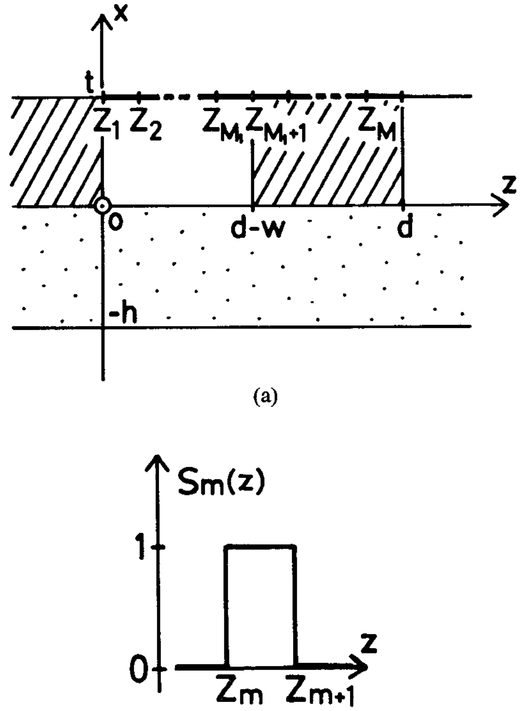

Fig. 3. Derivation of the boundary condition at $x = t$. (a) Division of the boundary $x = t$, $0 < z < d$. (b) Step function on the boundary.

where

$$\beta_n = \beta_0 + \frac{2n\pi}{d}$$

$$k_{xn}^{(a)} = \pm\left(k_0^2 - \beta_n^2\right)^{1/2}. \tag{6}$$

In the above expression, $\beta_0 \triangleq \beta - j\alpha$ is the eigenvalue of the periodic waveguide to be determined. The real part β is the phase constant of the fundamental space harmonic and the imaginary part α ($\alpha > 0$) is the attenuation constant due to leakage of the guided-wave energy into free space. The square root sign in (6) must be chosen so that [12]

$$\mathrm{Im}\left[k_{xn}^{(a)}\right] < 0 \qquad \text{for } n \geq 0$$

$$\left.\begin{array}{ll} \mathrm{Im}\left[k_{xn}^{(a)}\right] < 0 & \text{if } \mathrm{Re}[\beta_n] \leq 0 \\ \mathrm{Im}\left[k_{xn}^{(a)}\right] > 0 & \text{if } \mathrm{Re}[\beta_n] > 0 \end{array}\right\} \quad \text{for } n < 0.$$

After dividing the boundary $x = t$, $0 < z < d$ into M segments ($0 < z < d - w$ into M_1 segments, and $d - w < z < d$ into $M - M_1$ segments, see Fig. 3(a)), we express the fields ϕ and $\partial\phi/\partial n$ ($\partial/\partial n = \partial/\partial x$) on this boundary using the step functions $S_m(z)$ (see Fig. 3(b)) as

$$\phi = \sum_{m=1}^{M} u_m S_m(z) \tag{7a}$$

$$\frac{\partial \phi}{\partial n} = \sum_{m=1}^{M} q_m S_m(z) \tag{7b}$$

where

$$u_m = 0\ (M_1+1 \leqslant m \leqslant M) \qquad \text{for TE polarization}$$

$$q_m = 0\ (M_1+1 \leqslant m \leqslant M) \qquad \text{for TM polarization.}$$

From (5) and (7), we obtain at $x = t$

$$\sum_{m=1}^{M} u_m S_m = \sum_{n=-\infty}^{\infty} a_n e^{-j\beta_n z} \tag{8a}$$

$$v_g \sum_{m=1}^{M} q_m S_m = \sum_{n=-\infty}^{\infty} (-j) k_{xn}^{(a)} a_n e^{-j\beta_n z} \tag{8b}$$

where

$$v_g = \begin{cases} 1 & \text{for TE polarization} \\ 1/\epsilon_g & \text{for TM polarization.} \end{cases}$$

Truncating the infinite summation in the right-hand side of (8a) and (8b) into a summation of M terms (n runs from $-M/2$ to $M/2-1$ when M is even, and from $-(M-1)/2$ to $(M-1)/2$ when M is odd), and equating both sides of (8a) and (8b), respectively, at the midpoint of each segment, we can obtain the following matrix expressions:

$$\begin{pmatrix} u_1 \\ \vdots \\ u_M \end{pmatrix} = \begin{pmatrix} A_{1,-M_l} & \cdots & A_{1,M_u} \\ \vdots & & \vdots \\ A_{M,-M_l} & \cdots & A_{M,M_u} \end{pmatrix} \begin{pmatrix} a_{-M_l} \\ \vdots \\ a_{M_u} \end{pmatrix} \triangleq \begin{pmatrix} A \end{pmatrix} \begin{pmatrix} a_{-M_l} \\ \vdots \\ a_{M_u} \end{pmatrix}$$

$$\begin{pmatrix} q_1 \\ \vdots \\ q_M \end{pmatrix} = \frac{1}{v_g} \begin{pmatrix} A \end{pmatrix} \begin{pmatrix} K_{-M_l} & & 0 \\ & \ddots & \\ 0 & & K_{M_u} \end{pmatrix} \begin{pmatrix} a_{-M_l} \\ \vdots \\ a_{M_u} \end{pmatrix} \triangleq \begin{pmatrix} B \end{pmatrix} \begin{pmatrix} a_{-M_l} \\ \vdots \\ a_{M_u} \end{pmatrix}$$

where

$$A_{mn} = \exp\left(-j\beta_n \frac{z_m + z_{m+1}}{2}\right), \qquad K_n = -jk_{xn}^{(a)}$$

$$m = 1 \sim M, \quad n = -M_l \sim M_u$$

$$M_l = \begin{cases} M/2 & \text{when } M \text{ is even} \\ (M-1)/2 & \text{when } M \text{ is odd} \end{cases}$$

$$M_u = \begin{cases} M/2-1 & \text{when } M \text{ is even} \\ (M-1)/2 & \text{when } M \text{ is odd.} \end{cases}$$

$\boldsymbol{A}$ and $\boldsymbol{B}$ are square matrices of order M. Let the submatrices (of order M_1) of $\boldsymbol{BA}^{-1}$ and $\boldsymbol{AB}^{-1}$ be $\boldsymbol{C}_{\mathrm{TE}}$ and $\boldsymbol{C}_{\mathrm{TM}}$, respectively, as follows:

$$\begin{pmatrix} B \end{pmatrix}\begin{pmatrix} A^{-1} \end{pmatrix} = \left(\begin{array}{c|c} C_{\mathrm{TE}} & \\ \hline & \end{array}\right), \qquad \begin{pmatrix} A \end{pmatrix}\begin{pmatrix} B^{-1} \end{pmatrix} = \left(\begin{array}{c|c} C_{\mathrm{TM}} & \\ \hline & \end{array}\right).$$

The boundary condition imposed on the unknowns u_m and q_m ($m = 1 \sim M_1$) on the boundary $x = t$, $0 < z < d - w$ can be expressed as follows:

$$\begin{pmatrix} q_1 \\ \vdots \\ q_{M_1} \end{pmatrix} = \begin{pmatrix} C_{\mathrm{TE}} \end{pmatrix} \begin{pmatrix} u_1 \\ \vdots \\ u_{M_1} \end{pmatrix} \qquad \text{for TE polarization} \tag{9a}$$

$$\begin{pmatrix} u_1 \\ \vdots \\ u_{M_1} \end{pmatrix} = \begin{pmatrix} C_{\mathrm{TM}} \end{pmatrix} \begin{pmatrix} q_1 \\ \vdots \\ q_{M_1} \end{pmatrix} \qquad \text{for TM polarization.} \tag{9b}$$

C. Boundary Condition at $x = 0$

We express the field ϕ in the dielectric layer $-h < x < 0$ and in the lower half space $x < -h$, respectively, by

$$-h < x < 0: \quad \phi = \sum_{n=-\infty}^{\infty} \left\{ b_n \cos k_{xn}^{(r)} x + c_n \sin k_{xn}^{(r)} x \right\} e^{-j\beta_n z}$$

$$x < -h: \quad \phi = \sum_{n=-\infty}^{\infty} d_n e^{jk_{xn}^{(a)}(x+h)} e^{-j\beta_n z}$$

where

$$k_{xn}^{(r)} = \left(k_0^2 \epsilon_r - \beta_n^2\right)^{1/2}.$$

Since the tangential components of the electromagnetic fields are continuous at the boundary $x = -h$, we have

$$c_n = \frac{jk_{xn}^{(a)} - v_r k_{xn}^{(r)} \tan k_{xn}^{(r)} h}{v_r k_{xn}^{(r)} + jk_{xn}^{(a)} \tan k_{xn}^{(r)} h} b_n$$

where

$$v_r = \begin{cases} 1 & \text{for TE polarization} \\ 1/\epsilon_r & \text{for TM polarization.} \end{cases}$$

Hence, the field ϕ in $-h < x < 0$ is expressed by

$$\phi = \sum_{n=-\infty}^{\infty} \left\{ \cos k_{xn}^{(r)} x + \frac{jk_{xn}^{(a)} - v_r k_{xn}^{(r)} \tan k_{xn}^{(r)} h}{v_r k_{xn}^{(r)} + jk_{xn}^{(a)} \tan k_{xn}^{(r)} h} \sin k_{xn}^{(r)} x \right\} \cdot b_n e^{-j\beta_n z}. \tag{10}$$

We expand the fields ϕ and $\partial\phi/\partial n$ ($\partial/\partial n = -\partial/\partial x$) on the boundary $x = 0$, $0 < z < d$ using step functions as follows:

$$\phi = \sum_{m=1}^{M'} u'_m S_m(z)$$

$$\frac{\partial \phi}{\partial n} = \sum_{m=1}^{M'} q'_m S_m(z).$$

Equating the fields ϕ and $\partial\phi/\partial n$ given by the above expressions to ϕ and $\partial\phi/\partial n$ obtained from (10), and with a procedure similar to that in the preceding subsection, we have the boundary condition at $x = 0$ of the following

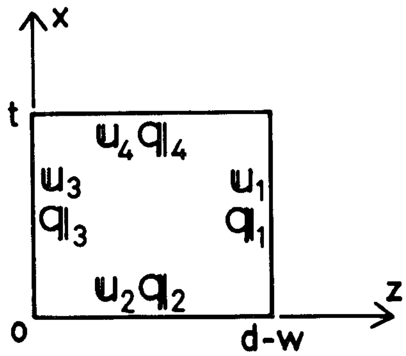

Fig. 4. Vectors with elements u_i and q_i on each side of L.

form:

$$\begin{pmatrix} q_1' \\ \vdots \\ q_{M_1'}' \end{pmatrix} = \begin{pmatrix} D_{TE} \end{pmatrix} \begin{pmatrix} u_1' \\ \vdots \\ u_{M_1'}' \end{pmatrix} \quad \text{for TE polarization} \qquad (11a)$$

$$\begin{pmatrix} u_1' \\ \vdots \\ u_{M_1'}' \end{pmatrix} = \begin{pmatrix} D_{TM} \end{pmatrix} \begin{pmatrix} q_1' \\ \vdots \\ q_{M_1'}' \end{pmatrix} \quad \text{for TM polarization.} \qquad (11b)$$

D. Characteristic Equation for TE Polarization

The vectors with elements u_i and q_i on each side of L are designated as shown in Fig. 4. Equations (4), (9a), and (11a) can be written, respectively, as

$$(\boldsymbol{G}_1 \quad \boldsymbol{G}_2 \quad \boldsymbol{G}_3 \quad \boldsymbol{G}_4)\begin{pmatrix} \boldsymbol{u}_1 \\ \boldsymbol{u}_2 \\ \boldsymbol{u}_3 \\ \boldsymbol{u}_4 \end{pmatrix} + (\boldsymbol{H}_1 \quad \boldsymbol{H}_2 \quad \boldsymbol{H}_3 \quad \boldsymbol{H}_4)\begin{pmatrix} \boldsymbol{q}_1 \\ \boldsymbol{q}_2 \\ \boldsymbol{q}_3 \\ \boldsymbol{q}_4 \end{pmatrix} = \boldsymbol{0} \qquad (12)$$

$$(\boldsymbol{q}_4) = (\boldsymbol{C}_{TE})(\boldsymbol{u}_4) \qquad (13)$$

$$(\boldsymbol{q}_2) = (\boldsymbol{D}_{TE})(\boldsymbol{u}_2). \qquad (14)$$

From the boundary condition at $z = 0$ and $z = d - w$, we have

$$(\boldsymbol{u}_3) = \boldsymbol{0} \qquad (15)$$

$$(\boldsymbol{u}_1) = \boldsymbol{0}. \qquad (16)$$

Eliminating unknowns by using (13)–(16), we can reduce (12) to

$$(\boldsymbol{G}_2 + \boldsymbol{H}_2\boldsymbol{D}_{TE} \quad \boldsymbol{G}_4 + \boldsymbol{H}_4\boldsymbol{C}_{TE} \quad \boldsymbol{H}_1 \quad \boldsymbol{H}_3)\begin{pmatrix} \boldsymbol{u}_2 \\ \boldsymbol{u}_4 \\ \boldsymbol{q}_1 \\ \boldsymbol{q}_3 \end{pmatrix} \triangleq (\boldsymbol{F}_{TE})\begin{pmatrix} \boldsymbol{u}_2 \\ \boldsymbol{u}_4 \\ \boldsymbol{q}_1 \\ \boldsymbol{q}_3 \end{pmatrix} = \boldsymbol{0}$$

where $\boldsymbol{F}_{TE}$ is a square matrix whose order is equal to the number of the segments into which L is divided. The characteristic equation which determines the eigenvalue β_0 is

$$\det(\boldsymbol{F}_{TE}) = 0.$$

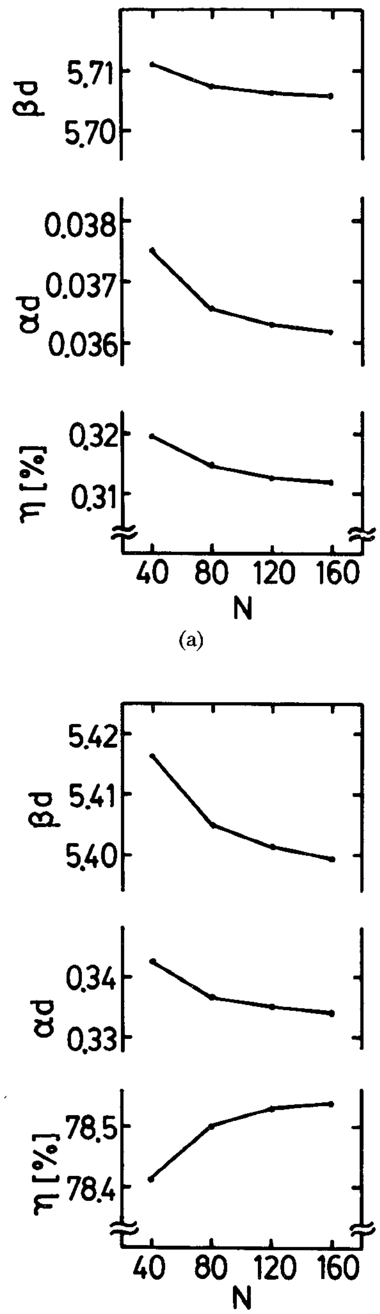

Fig. 5. Convergence of the solution. $\epsilon_r = 11.8$, $\epsilon_g = 1.0$, $h = 0.5d$, $k_0 d = 2.1$, $w = 0.5d$, $t = 0.5d$. (a) TE_0 mode. (b) TM_0 mode.

The corresponding characteristic equation for TM polarization can be obtained in similar fashion.

III. Numerical Results

In the numerical calculations in this section, we assume that the medium of the dielectric slab is high-resistivity silicon with $\epsilon_r = 11.8$, normalized slab thickness $h/d = 0.5$, and normalized frequency $k_0 d = 2.1$. We concentrate our calculations on the fundamental TE and TM modes (TE_0 and TM_0 modes). For the waveguide dimensions and the frequency assumed in our calculations, only the space harmonic of $n = -1$ propagates away from the waveguide.

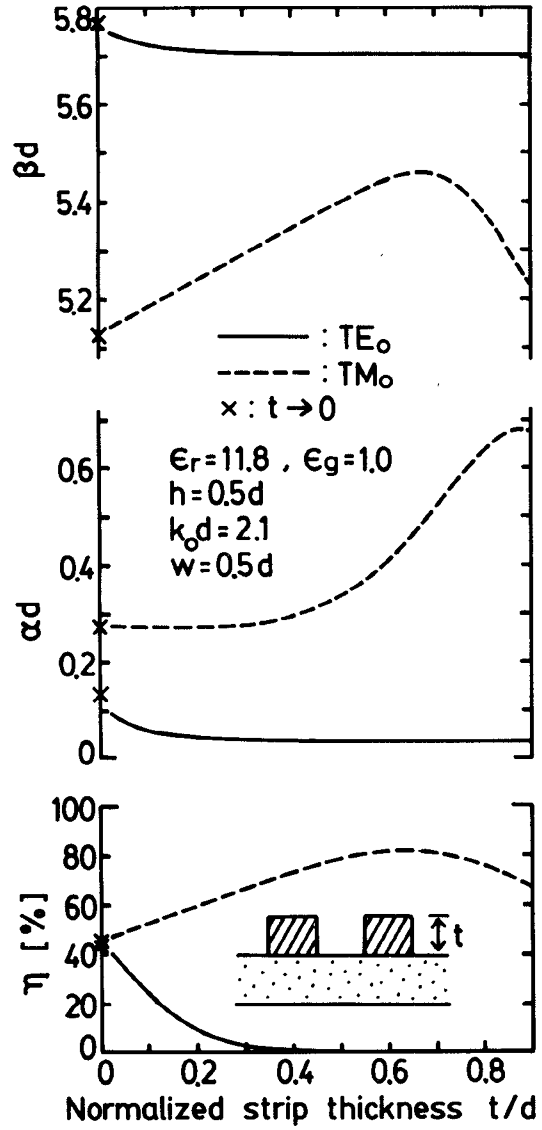

Fig. 6. Phase constant β, leakage constant α, and partition of radiated power η versus strip thickness t.

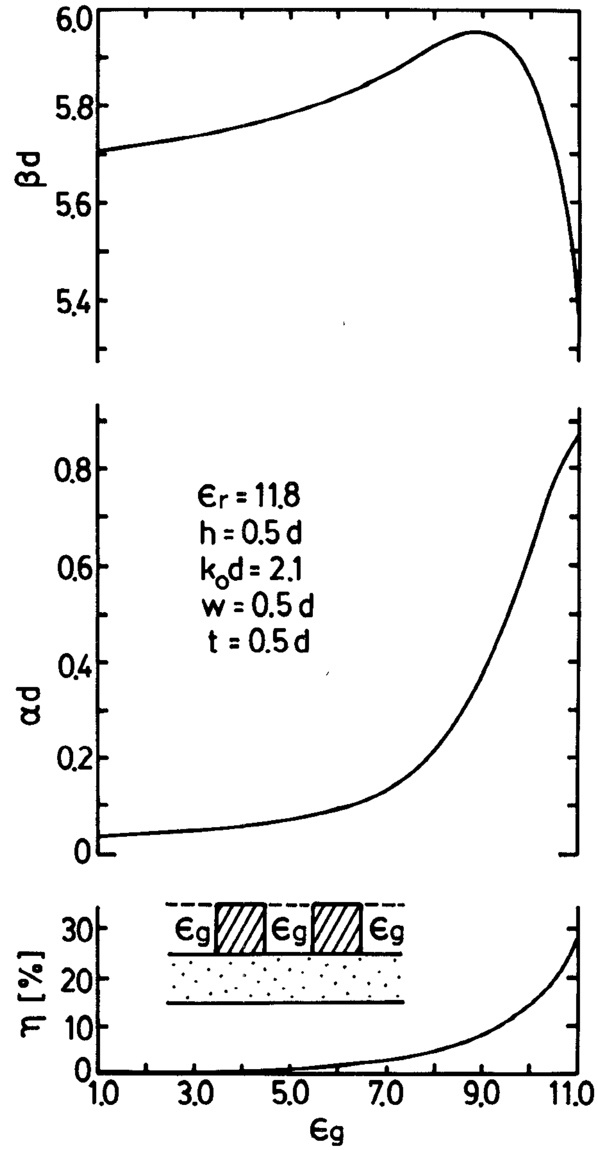

Fig. 7. Effect of the value of ϵ_g on the radiation characteristics of the TE_0 mode.

Fig. 5 shows the convergence of the solution $\beta_0 = \beta - j\alpha$ and η with an increasing number of the segments N, where all the segments have equal length. Here, η, the ratio of the power radiated into the upper half space to the total radiated power, is defined by [13]

$$\eta = \frac{|a_{-1}|^2}{|a_{-1}|^2 + |d_{-1}|^2}.$$

From Fig. 5, the convergence is found to be good for both polarizations.

Fig. 6 shows a plot of βd, αd, and η as a function of the normalized metal-strip thickness t/d. We also calculated those values for $t \to 0$ with the method described in [7][2] and plotted them on the axis $t/d = 0$ in Fig. 6. From this figure, it can be seen that β and α of the TE_0 mode take constant values for t/d larger than 0.3. This is because the electromagnetic fields of this polarization cannot propagate (being evanescent, instead) along the $+x$ direction between the metal strips for $d - w = 0.5d$ at $k_0 d = 2.1$, so that further increases of t/d beyond a certain value have little effect on the field guided along the dielectric slab. Owing to the decay of the fields mentioned above, η decreases to zero with increasing t/d. For TM polarization, on the other hand, electromagnetic fields can propagate as a TEM wave along the x direction between the strips. Therefore, as t/d increases, more energy is stored between the strips and larger power is radiated in the upward as well as downward directions away from the waveguide. The leakage constant of the TM_0 mode is about 18 times larger than that of the TE_0 mode for $t/d = 0.8$ in Fig. 6. This property is useful in constructing a mode filter for millimeter- and submillimeter-wave integrated circuits.

The effect of relative permittivity ϵ_g of the medium between the metal strips on the radiation characteristics

[2]We used subsectional step functions as both the expanding functions for the surface current density over the strip and the weighting functions.

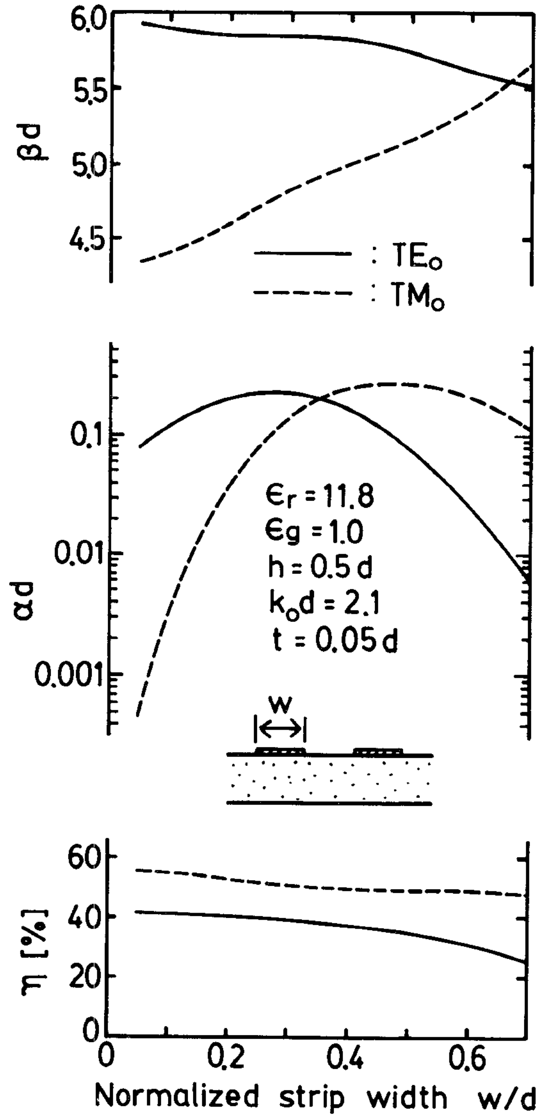

Fig. 8. Phase constant β, leakage constant α, and partition of radiated power η versus strip width w.

for TE polarization is shown in Fig. 7. From this figure, it is found that a larger value of ϵ_g permits larger power to radiate. The lowest-order TE mode supported by the parallel-plate waveguide corresponding to the region between the strips can propagate along the $+x$ direction when $\epsilon_g > 8.95$. The leakage constant of the TE_0 mode for $\epsilon_g = 8.95$ is approximately equal to that of the TM_0 mode for $\epsilon_g = 1.0$.

Fig. 8 shows a plot of βd, αd, and η as a function of the normalized strip width w/d for $t/d = 0.05$. The maximum leakage occurs at $w/d = 0.27$ for the TE_0 mode, and at $w/d = 0.48$ for the TM_0 mode. In this figure, it should be noted that the leakage constant α does not seem to vanish even if the strip width w decreases to zero for the TE_0 mode whose electric field lies parallel to the strips.

IV. Conclusions

We have analyzed theoretically the radiation characteristics of a dielectric slab waveguide periodically loaded with thick metal strips. The leakage constant, the phase constant of the fundamental space harmonic, and the partition of power radiated into the upper and the lower half spaces have been calculated numerically for both the TE_0 and TM_0 modes. It has been found that the leakage constant of the TM_0 mode is much larger than that of the TE_0 mode. This property will find application in mode filters for millimeter- and submillimeter-wave integrated circuits.

The analysis method employing a boundary-integral-equation formulation as presented in this paper is useful in analyzing periodic waveguides with metal strips of arbitrary cross section and corrugated dielectric waveguides having an arbitrary groove profile [14], [15].

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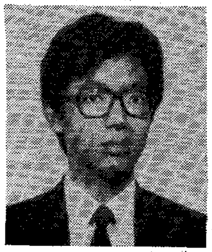

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