Characteristics and Design Consideration of Leaky-Wave NRD-Guides for Use as Millimeter-Wave Antenna

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***Abstract*—Leaky-wave characteristics of a class of nonradiative dielectric (NRD)-guides with various shapes of trapezoidal cross section are systematically studied for their potential applications in low-cost millimeter-wave antennas. A numerical technique is applied to model these irregular structures. The technique is formulated by effectively combining a multimode network theory with a mode-matching method. Our emphasis in this work is on the investigation of parametric effects in connection with the trapezoidal dimensions on leakage properties of the NRD-guide. Extensive results are presented to derive some useful guidelines for the design considerations of new types of NRD-guide leaky-wave antennas.**

***Index Terms*— CAD, field modeling, leaky-wave propagation, millimeter-wave antenna, multimode network theory, nonradiative dielectric (NRD)-guide.**

I. Introduction

NONRADIATIVE DIELECTRIC (NRD)-guides were first proposed for use in antenna design and applications at millimeter wavelengths in 1981 by Yoneyama and Nishida [1]. As it is well known, waveguide losses increase significantly as frequency increases and usual antenna structures become more difficult to fabricate in view of the reduced size. Leaky NRD waveguides show a great promise to overcome these problems. In addition, the NRD-guide leaky-wave antenna is also attractive because of its easy fabrication at millimeter-wave bands by simply introducing asymmetry in the cross section of the guide. This asymmetry is responsible for the leaky-wave generation, suggesting that a thorough understanding of its parametric effects is vital for an adequate design of a leaky-wave antenna. Several forms of leaky NRD waveguide structures have been suggested for millimeter-wave applications [2], [3]. Oliner *et al.* have studied in depth the leakage properties of NRD-guide with rectangular profiles [3], [4].

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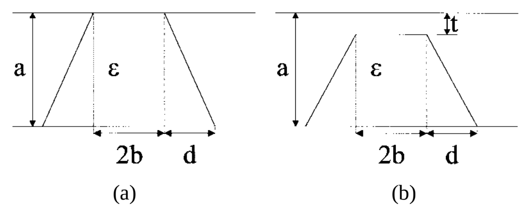


Fig. 1. Trapezoidal cross-sectional view of two new NRD guide leaky-wave structures proposed for low-cost millimeter-wave antenna applications. (a) Without gap. (b) With gap.

In this paper, two new types of leaky-wave NRD-guide with trapezoidal cross sections, which are believed to give more flexibility in antenna design, are analyzed in a comprehensive and accurate way. One is full-filled without a gap as shown in Fig. 1(a), while the other is with a gap between the top metal plate and the dielectric strip in the NRD guide, as shown in Fig. 1(b). The two new structures provide more flexibility in the design of a leaky-wave antenna by changing the geometric dimensions of the structures. Also, these antennas may be more practical because keeping an exact rectangular shape during manufacturing could be very difficult.

Our field-theory-based analysis given here permits one to gain insight into qualitative effects produced by the size d and also to determine how large d can be before it starts to have an influence on transmission properties of the NRD-guide as a millimeter-wave guiding structure. Although measurements for the leaky-wave antenna as shown in Fig. 1(a) are available [5], parameter optimization of the structure has not been accomplished yet, and no theory is available to date for the two new NRD-guide leaky-wave antennas [6]. In our studies, it is shown that the parametric effects are rather complex and accurate theoretical prediction is absolutely required for the design considerations of any successful NRD-guide leaky-wave antenna.

In the present study, a multimode network theory combined with a mode-matching method is used to analyze leaky properties of the two proposed types of leaky-wave NRD-guide antennas. To simplify our mathematical analysis, a staircase approximation is applied to discretize the trapezoidal profile that copes with the model requirement. Numerical results obtained by using this technique provide not only a useful guideline for the design of such new antennas, but also give a wealth of information in relation to the fabrication tolerances in the design of NRD-guides as a transmission line.

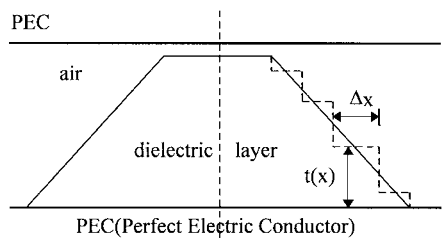


Fig. 2. Staircase approximation of trapezoidal dielectric profile.

II. Theoretical Analysis

Leaky guided-wave characteristics of NRD-guides having irregular cross-sectional shapes are known to be not amenable to an exact field analysis, even for a relatively simple geometric profile. Therefore, an approximate but accurate modal analysis must be resorted to. In particular, a method is required that would be generally applicable to different profiles of structures. This is important for a comparative study of various useful structures with consistent result accuracy. We find that a method using the staircase approximation can be effectively applied to the analysis of leaky-wave structures of any profile.

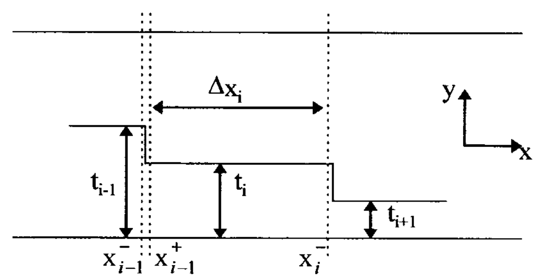
Fig. 2 depicts the approximation of a continuous trapezoidal profile by a piecewise constant step that is known as the staircase approximation. It is a discretization in geometry, obviously, that in the limiting case of vanishing step size, the piecewise constant profile will approach the continuous one. Therefore, calculated results generated by such a model should converge to that representing the electrical behavior of the real physical geometry as the step size is decreased. With such an approximation, mathematical analysis and physical interpretation on the potential mode coupling phenomena related to the leaky-wave structure can be kept simple and clear.

With the piecewise constant profile, the cross section of NRD-guide may be viewed as a series of step discontinuities connected by a length of uniform waveguide. The equivalent network for a step discontinuity may therefore be utilized to analyze the leaky characteristics of such an antenna, as the complete set of discrete eigenvalues and their corresponding modal functions can be easily calculated for a uniform parallel-plate waveguide with partially-filled dielectric slab.

Fig. 3 describes a basic unit that consists of a step discontinuity between two uniform waveguides at the point x_{i-1} and a uniform waveguide of length Δx_i between the two points x_{i-1} and x_i. Scattering of waves by such a step discontinuity between two uniform waveguides has been rigorously formulated [7]. For completeness and simplicity, the procedure of analysis is briefly outlined as follows.

In the region between x_{i-1}^{+} and x_i^{-}, tangential field components of the total fields in the discretized NRD-guide can be expressed by

$$E_y(x, y) = j \sum_{n=1}^{\infty} V_n''(t_i, x)\phi_n''(t_i, y)\, \frac{1}{\varepsilon(t_i, y)} \tag{1}$$



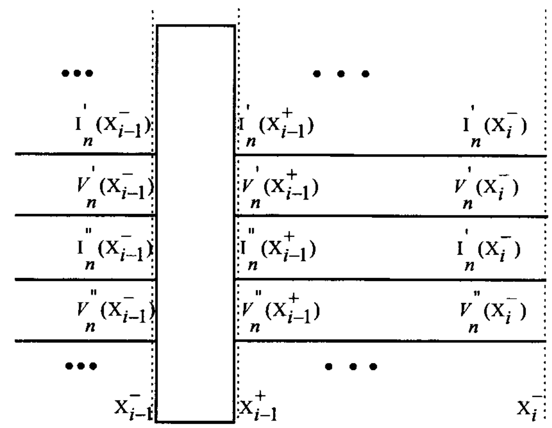


Fig. 3. Equivalent network of modal representation for a step discontinuity.

$$E_z(x, y) = -\left(\sum_{n=1}^{\infty} V_n'(t_i, x)\phi_n'(t_i, y) + \sum_{n=1}^{\infty} V_n''(t_i, x)\psi_n''(t_i, y)\right) \tag{2}$$

$$H_y(x, y) = -\sum_{n=1}^{\infty} I_n'(t_i, x)\phi_n'(t_i, y) \tag{3}$$

$$H_z(x, y) = -j\left(\sum_{n=1}^{\infty} I_n'(t_i, x)\psi_n'(t_i, y) + \sum_{n=1}^{\infty} I_n''(t_i, x)\phi_n''(t_i, y)\right) \tag{4}$$

where the $e^{-jk_z z}$ factor is suppressed in the above equations. ϕ_n' and ϕ_n'' are the eigen modal functions for LSM and LSE modes, respectively. They can be determined by using a transmission line method. Here, we employ such simplified notations as

$$\psi_n'(t_i, y) = \frac{k_z}{k_{un}'^2}\,\frac{d}{dy}\,\phi_n'(t_i, y)$$
$$\psi_n''(t_i, y) = \frac{k_z}{k_{un}''^2}\,\frac{d}{\varepsilon(t_i, y)\,dy}\,\phi_n''(t_i, y) \tag{5}$$

in which k_{un}' and k_{un}'' present wavenumbers of the nth LSE and LSM modes, respectively. At the step discontinuity of $x = x_i$, the tangential field components E_y, E_z, H_y, H_z must be continuous. From (1)–(4), we derive a set of equations as follows:

$$\sum_{n=1}^{\infty} V_n''(t_i, x_i)\phi_n''(t_i, y)\frac{1}{\varepsilon(t_i, y)} = \sum_{n=1}^{\infty} V_n''(t_{i+1}, x_i)\phi_n''(t_{i+1}, y)\frac{1}{\varepsilon(t_{i+1}, y)} \quad (6)$$

$$\sum_{n=1}^{\infty} V_n'(t_i, x_i)\phi_n'(t_i, y) + \sum_{n=1}^{\infty} V_n''(t_i, x_i)\psi_n''(t_i, y) = \sum_{n=1}^{\infty} V_n'(t_{i+1}, x_i)\phi_n'(t_{i+1}, y) + \sum_{n=1}^{\infty} V_n''(t_{i+1}, x_i)\psi_n''(t_{i+1}, y) \quad (7)$$

$$\sum_{n=1}^{\infty} I_n'(t_i, x_i)\phi_n'(t_i, y) = \sum_{n=1}^{\infty} I_n'(t_{i+1}, x_i)\phi_n'(t_{i+1}, y) \quad (8)$$

$$\sum_{n=1}^{\infty} I_n'(t_i, x_i)\psi_n'(t_i, y) + \sum_{n=1}^{\infty} I_n''(t_i, x_i)\phi_n''(t_i, y) = \sum_{n=1}^{\infty} I_n'(t_{i+1}, x_i)\psi_n'(t_{i+1}, y) + \sum_{n=1}^{\infty} I_n''(t_{i+1}, x_i)\phi_n''(t_{i+1}, y). \quad (9)$$

It can be easily proved that the eigen modal functions ϕ_n' and ϕ_n'' satisfy the following orthogonal relation:

$$\langle \phi_m' | \phi_n' \rangle = \delta_{mn} \quad (10)$$

$$\left\langle \phi_m'' \middle| \frac{1}{\varepsilon(t_i, y)} \middle| \phi_n'' \right\rangle = \delta_{mn}. \quad (11)$$

Scalar inner product of (6)–(9) with either ϕ_n' or ϕ_n'' and subsequent use of the orthogonality relation (10) and (11) lead to the following relationships:

$$V'' = P''\overline{V}'' \quad (12)$$

$$V' + R''V'' = Q'\overline{V}' + S''\overline{V}'' \quad (13)$$

$$I' = P'\overline{I}' \quad (14)$$

$$R'I' + I'' = S'\overline{I}' + Q''\overline{I}'' \quad (15)$$

where V' and I' are column vectors whose elements are the transmission line voltage and current of the nth LSE mode, denoted as $V_n'(x_i)$ and $I_n'(x_i)$. Similar definitions hold for $V''$and I'' for the LSM modes, and also for those vectors with bar. P', Q', R', and S' are matrices that characterize the coupling of modes at the discontinuity and their elements are defined by scalar products of modal functions on the two sides of the discontinuity as follows:

$$\begin{aligned} P'_{mn} &= Q'_{mn} = \langle \phi_m' | \overline{\phi}'_n \rangle \\ P''_{mn} &= \left\langle \phi_m'' \middle| \frac{1}{\varepsilon(t_{i+1}, y)} \middle| \overline{\phi}'_n \right\rangle \\ Q''_{mn} &= \left\langle \phi_m'' \middle| \frac{1}{\varepsilon(t_i, y)} \middle| \overline{\phi}'_n \right\rangle \\ R'_{mn} &= \left\langle \phi_m'' \middle| \frac{1}{\varepsilon(t_i, y)} \middle| \psi_n' \right\rangle \\ R''_{mn} &= \langle \phi_m' | \psi_n'' \rangle \\ S'_{mn} &= \left\langle \phi_m'' \middle| \frac{1}{\varepsilon(t_i, y)} \middle| \overline{\psi}'_n \right\rangle \\ S''_{mn} &= \langle \phi_m' | \overline{\psi}''_n \rangle \end{aligned}$$

for any $m, n = 1, 2, 3, \cdots$. It is obvious from the above scalar product equations that the matrices P' and Q' are responsible for the coupling among modes of the same polarization, whereas R' and S' are responsible for the cross-coupling among modes of the opposite polarization. Also, it can be proved that the following matrix identities hold [8]:

$$P'^T Q' = Q'^T P' = 1 \quad (16)$$

$$P''^T Q'' = Q''^T P'' = 1 \quad (17)$$

$$R' = -R''^T \quad (18)$$

$$S' = Q''\overline{R}' \quad (19)$$

$$S'' = Q'\overline{R}'' \quad (20)$$

where 1 is the unit matrix and T stands for matrix transpose. Using (12)–(15) and the above matrix identities, the relationship between the voltage and current on both sides of the ith step discontinuity may be expressed in terms of coupling matrices as

$$V = Q_i\overline{V} \quad (21)$$

$$I = P_i\overline{I} \quad (22)$$

where $V, I, \overline{V}, \overline{I}, Q_i$, and P_i are defined by

$$V = \begin{bmatrix} V'' \\ V' \end{bmatrix} \qquad \overline{V} = \begin{bmatrix} \overline{V}'' \\ \overline{V}' \end{bmatrix} \quad (23)$$

$$I = \begin{bmatrix} I'' \\ I' \end{bmatrix} \qquad \overline{I} = \begin{bmatrix} \overline{I}'' \\ \overline{I}' \end{bmatrix} \quad (24)$$

$$Q_i = \begin{bmatrix} P'' & 0 \\ S'' - R''P'' & Q' \end{bmatrix} \quad (25)$$

$$P_i = \begin{bmatrix} Q'' & S' - R'P' \\ 0 & P' \end{bmatrix}. \quad (26)$$

It can be straightforward to show that the super-matrices P_i and Q_i satisfy the following identity:

$$P_i^T Q_i = Q_i^T P_i = 1. \quad (27)$$

From (21), (22), and (27), it can be deduced that the input impedance matrix $Z(x_i^-)$ at the $x = x_i^-$ plane looking into the right side satisfies

$$Z(x_i^-) = Q_i Z(x_i^+) Q_i^T. \quad (28)$$

The reflection coefficient matrix at the $x = x_i^-$ plane looking into the right side can be obtained by

$$\Gamma(x_i^-) = \left[Z(x_i^-) + Z_{ci}\right]\left[Z(x_i^-) - Z_{ci}\right]. \quad (29)$$

In the uniform waveguide region between x_{i-1}^{+} and x_i^{-}, each mode propagates independently and it can be represented by a transmission line section. Thus, the input impedance matrix at the $x = x_{i-1}^{+}$ plane looking into the right side is determined by the impedance transform technique [8]

$$Z(x_{i-1}^{+}) = Z_{ci}[1 + H_i \Gamma_i H_i][1 - H_i \Gamma_i H_i]^{-1} \quad (30)$$

where Z_{ci} and H_i are, respectively, the characteristic impedance and phase matrices of the nth step discontinuity. They are all diagonal matrices whose elements are

$$\begin{aligned} (Z_{ci})_{mn} &= \delta_{mn} Z_{cin} \\ (H_i)_{mn} &= \delta_{mn} \exp(-jk_{xin}\Delta x_i). \end{aligned} \quad (31)$$

Finally, one plane is selected as a reference plane and the above equations are used repeatedly to calculate the impedance matrix at the reference plane looking into the right side for $\overleftarrow{Z}$ and looking into the left side for $\overrightarrow{Z}$. According to the generalized transverse-resonance relation, we have then the following equation:

$$\det\left(\overleftarrow{Z} + \overrightarrow{Z}\right) = 0. \quad (32)$$

This determinant equation (32) governs the dispersion relation from which the leaky-wave characteristics of the irregular NRD-guide can be completely determined by searching for complex roots of the transcendental equation (32).

III. Numerical Results and Discussion

In order to quantify the leaky-wave characteristics of NRD-guide for various shapes of trapezoidal cross section, the developed model is applied to generate a large amount of numerical results involving parametric effects. Let us first consider the leaky-wave antenna structure shown in Fig. 1(a), which may be also used as an array feeder structure. When d tends to be null, the structure becomes a normal uniform NRD-guide, there is no leakage if the design rule of a standard NRD-guide is applied. As d increases from zero, an asymmetry is introduced, and a small amount of vertical electric field is thus created, which produces a mode in the parallel plate (air region) akin to a TEM mode. This mode then propagates at an angle between the parallel plates until it reaches the open end and leaks away into space.

The effect of dimension d on leakage constant and normalized propagation constant (or effective permittivity) is plotted in Fig. 4. We note that there appear three main features as d increases. First, when d is zero, the structure becomes a normal uniform NRD-guide, no leakage occurs because no coupling between the eigen modes in the NRD guide through the dielectric-air interface. When d increases from zero, the leakage becomes significant and increases sharply till it reaches its maximum, then it decreases as d increases further. This phenomenon is due to the coupling between the LSE and LSM modes through the sloping dielectric-air interface. Second, we observe a dip in the vicinity of $d/\lambda_0 = 0.45$ (for $b/\lambda_0 = 0.2$); it is also physically due to the cancellation effect [9]. The third main feature is that there is a second peak in the leakage curve. This phenomenon is attributed to the fact that when the leakage reaches the first peak, the coupling between the LSE and LSM modes does not reach its maximum. The decreasing of the leakage after the first peak is due completely to the cancellation effect. The second peak is also the synthesis of the maximum coupling and the cancellation effect. It can be observed that the cancellation effect actually reduces the maximum leakage. The decreasing of the leakage after the second peak is because of the weakening of the coupling between modes with d increasing further.

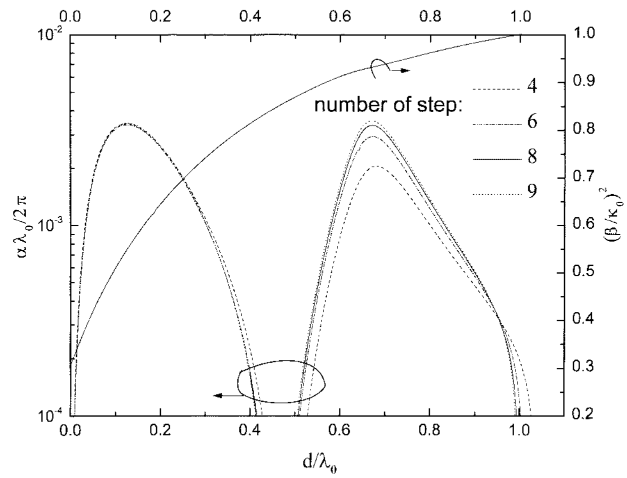


Fig. 4. Effect of dimension d on the (normalized) leakage constant $\alpha\lambda_0/2\pi$ and propagation constant $(\beta/k_0)^2$ for leaky-wave NRD structure without a gap, as shown in Fig. 1(a) with $a/\lambda_0 = 0.423$, $b/\lambda_0 = 0.2$, $\varepsilon = 2.56$. Typical convergence behavior is also presented herewith with respect to the number of steps chosen in the numerical calculations.

Since in the present calculations the sloping line of the structure is geometrically discretized by the staircase approximation, the convergence property of the step number is one of the most important factors in the calculation. Fig. 4 also shows the convergence behavior for the calculated results. It is found that as long as the step number is larger than eight, the results calculated are good enough for practical use. For a small dimension of d, for instance, in the first peak region, even four steps are good enough to obtain accurate results. Fig. 4 also indicates that when d/λ_0 is less than 0.09 (for $b/\lambda_0 = 0.2$), the leakage can be neglected, and d will not affect the performance of NRD-guide as a normal transmission structure. Of course, the convergence of results with the number of the modes used in the mode-matching procedure must be carefully verified in the calculation because an infinite summation of modes formulated in the dispersion relation (32) has to be truncated for numerical analysis. Our practice reveals that only 30 eigen modes used in the mode matching calculation are good enough to generate accurate results. From Fig. 4, we can see that β increases as d/λ_0 increases. This is because the larger the d value, the larger the effective dielectric constant.

Fig. 5 presents the variations in leakage as a function of d/λ_0 with b/λ_0. The variations are all calculated by discretizing the dielectric sloping line to nine steps so that the accuracy of the calculation is guaranteed. By comparing the four curves obtained for different b, two main features are observed. One is that the first peak decreases rapidly as b increases. When $b/\lambda_0 = 0.33$, the first peak even disappears. The other is that the second peak becomes larger as b increases,

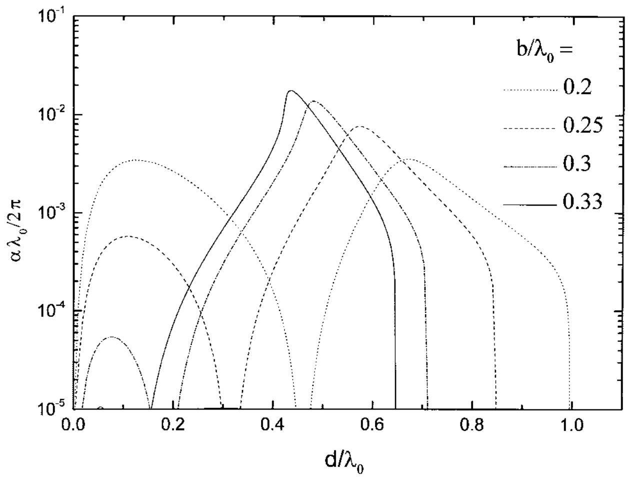


Fig. 5. Characteristic variation and parametric effects of $\alpha\lambda_0/2\pi$ as a function of d/λ_0 with b/λ_0 as a parameter for the structure without a gap, and $a/\lambda_0 = 0.423$, $\varepsilon = 2.56$.

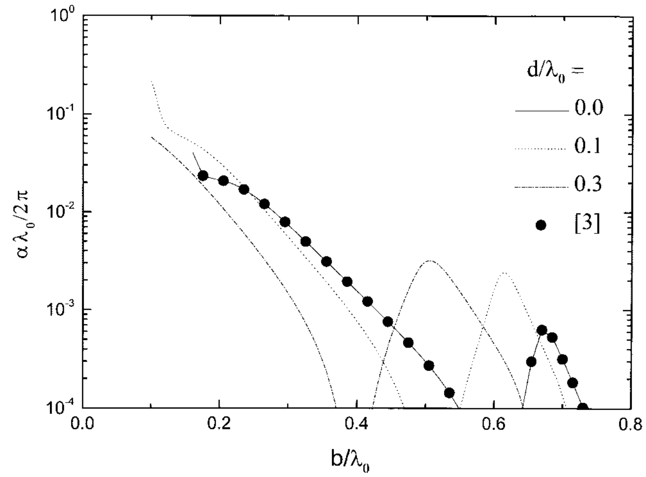


Fig. 7. Characteristic variation and parametric effects of leakage constant against b/λ_0 with d/λ_0 as a parameter for the structure with a gap and $a/\lambda_0 = 0.423$, $t/\lambda_0 = 0.08$, $\varepsilon = 2.56$. Comparison of our calculated results is made with [3].

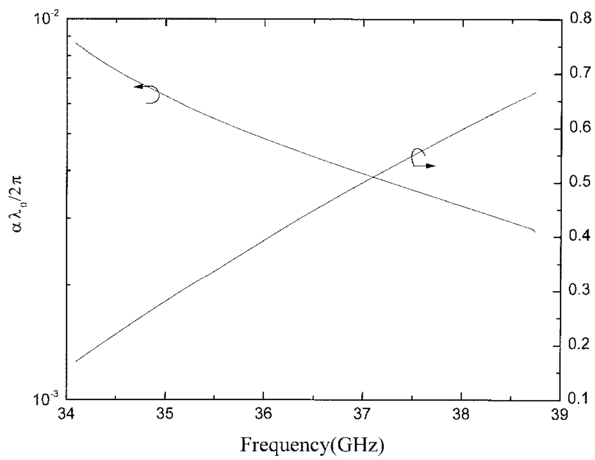


Fig. 6. Dispersion characteristics of the leakage and propagation constants for the structure without a gap and with $a = 3.384$, $b = 1.6$, $d = 1.008$, $\varepsilon = 2.56$.

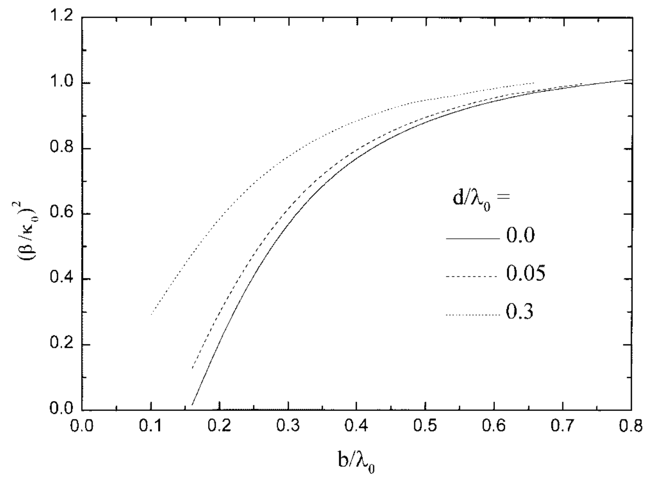


Fig. 8. Characteristic curves of effective dielectric constant as a function of b/λ_0 with d/λ_0 as a parameter for the structure with a gap, and $a/\lambda_0 = 0.423$, $t/\lambda_0 = 0.08$, $\varepsilon = 2.56$.

and the dimension d where the leakage constant reaches its maximum decreases. These two features can be interpreted by the coupling between modes and the cancellation effect. When b increases, the point where the cancellation effect occurs will undergo a shift to the left side, i.e., the larger the b, the smaller the d where the cancellation effect occurs. However, the effect of changing b on the maximum mode coupling is not as significant as the cancellation effect. That is why the first peak decreases rapidly while the second peak increases slower. From Fig. 5 we can also infer that when b is less than $0.2\lambda_0$, the largest leakage will occur in the first peak, and a relatively small increase of d from zero will produce significant leakage. The smaller the b, the smaller the d needed to generate significant leakage. When b is greater than $0.33\lambda_0$, the leakage is negligible if d is less than $0.18\lambda_0$. This observation is rather helpful for determining the manufacturing tolerances for the transmission waveguide.

In Fig. 6, the leakage and propagation constants are plotted as a function of frequency, where the central frequency is selected to be 37.5 GHz. The geometrical parameters are the same given in the inset of Fig. 4, and $d/\lambda_0 = 0.126$ is selected in order to obtain maximum leakage. We can observe that the propagation constant increases linearly as the frequency increases and that the leakage decreases slightly as the frequency increases. This is a very desirable feature because it ensures a stable radiation pattern with low distortions as the frequency scanning effect is minimized. In other words, such a linear behavior gives rise to a possibility of having a stationary-directed power radiation pattern if frequency operates over this linear window.

From Figs. 7–9, the leaky-wave characteristics are given for antenna structures having a gap. Fig. 7 shows variations of $\alpha\lambda_0/2\pi$ as a function of b/λ_0 with d/λ_0 as a parameter. When d vanishes, we get exactly the same results given in [3], indicated with "•". It can be seen from the curves that there are two main features. One is a general decrease in the value of α as b increases. This is because as b increases, the mode coupling is reduced and therefore the leakage power decreases. The other is the presence of a dip in the vicinity of certain b.

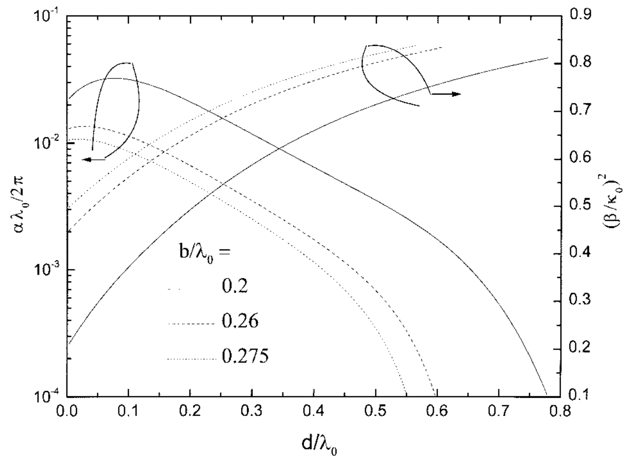


Fig. 9. Curve plots of the leakage and propagation constants as a function of d/λ_0 with b/λ_0 as a parameter for the structure with gap, and with $a/\lambda_0 = 0.423$, $t/\lambda_0 = 0.08$, $\varepsilon = 2.56$.

It is again due to the cancellation effect [9]. When d increases, we note that the cancellation will occur at a smaller b. This is because the existence of d can be viewed as an additional increase of b, therefore the larger the d, the smaller the b where the cancellation occurs. Fig. 8 presents the curves of $(\beta/\kappa_0)^2$ as a function of b/λ_0 with d/λ_0 as a parameter. It shows that as either b or d increases, the propagation constant will increase monotonously. This can be expected as the increasing of either b or d causes the increase of the effective dielectric constant of the guided-wave antenna structure.

Fig. 9 describes variations of leakage and normalized propagation constant as a function of d/λ_0 with b/λ_0 as a parameter. It indicates that when b/λ_0 is greater than 0.275, the antenna with trapezoidal profile for $d = 0$ (rectangular shape) gives larger leakage than for $d > 0$, while if b/λ_0 is smaller than 0.275, the leakage will increase first up to its maximum and then decrease as d increases further. It also shows that the leakage could be enhanced if both b and d becomes smaller if the other dimensions are chosen in an appropriate manner. This information can help to select the value of d to give a maximum leakage once b is chosen in this type of antenna design.

IV. Conclusion

Leaky-wave and propagation characteristics of NRD-guides are studied systematically for various shapes of trapezoidal cross section. A multimode network theory combined with a rigorous mode-matching procedure is developed. This is done by applying the staircase approximation of an irregular NRD-guide shape in the proposed field model. This technique allows efficient and accurate modeling of leaky-wave NRD structures of virtually any profile. It is found that fast convergence can be easily made without making a compromise on numerical accuracy. Emphasis in our study is placed on the parametric effects of the trapezoidal geometry on the leakage of NRD-guides since an asymmetric profile is responsible for generating this leakage. Numerical results are obtained to describe leaky properties of a class of structures. Interesting features are observed for two new types of leaky-wave NRD-guides with and without an air gap. Useful guidelines can be extracted from the present analysis for the design of new types of NRD-guide leaky wave antennas. Techniques are also discussed for maintaining the frequency dispersionless leakage of leaky- wave NRD-guide antennas (or minimizing frequency scanning effects) and for maximizing the fabrication tolerances of NRD-guides.

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