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DESIGN OF LAYERED RIDGE DIELECTRIC WAVEGUIDE FOR MILLIMETER AND SUB-MILLIMETER WAVE CIRCUITS

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Abstract

Design rules for Layered Ridge Dielectric Waveguide (LRDW) are presented for the first time through simple figures and closed form equations. The Effective Dielectric Constant (EDC) method is used to develop the design rules that account for typical circuit specifications such as higher order mode suppression, dispersion, attenuation, and coupling between adjacent transmission lines. Comparisons between the design of LRDW, image guide, and millimeter-wave dielectric ridge guide are made.

Keywords:Dielectric waveguide, image guide, insulated image guide, millimeter-wave waveguides

1. Introduction

Most millimeter and sub-millimeter wave circuits developed to date have relied on the extension of microwave transmission lines such as microstrip and coplanar waveguide on thin substrates, but these transmission lines have several disadvantages. The surface resistivity of the metal lines increases as $\sqrt{f}$ [1] and the transmission line geometry and substrate thickness must decrease as $1/f$ to maintain a single mode transmission line and minimize leakage and dispersion. The result is that the conductor loss per guided wavelength increases with frequency while the dielectric and radiation loss per guided wavelength remain nearly constant.

To eliminate the high conductor loss, dielectric waveguides have been developed. They do not require metallic lines or ground planes to guide the electromagnetic energy, but instead they use the difference in permittivity between two or more materials to propagate the excited waves. Practical implementation of the waveguides often necessitates a ground plane for mechanical support and heat sinking. However, since the current is distributed over a wider area on the ground plane than the microstrip line or the center strip of coplanar waveguide, the conductor loss is greatly reduced. Examples of dielectric waveguides that have been reported are Image Guide[2] , Insulated Image Guide[3] , Millimeter-wave Dielectric Ridge Guide[4] , and Layered Ridge Dielectric Waveguide (LRDW)[5] .

Image guide, insulated image guide, and millimeter-wave dielectric waveguide have been well documented in the literature and design procedures have been reported for each waveguide [4] [6] [7] . Although, LRDW has been analyzed theoretically [5] [8] , LRDW directional couplers have been characterized using the Finite Difference Time Domain method[9] , transitions between rectangular waveguide and LRDW have been developed and modeled using the EDC method[10] , and LRDW leaky wave antennas have been demonstrated[11] , design procedures for LRDW have not been presented. This paper presents design rules and procedures for LRDW that may be used to optimize the waveguide performance over a specified bandwidth. When possible, closed form equations or charts are given for the design parameters. In addition, comparisons between LRDW and other dielectric waveguides will be given.

2. LRDW Description and Design Criteria

LRDW consists of a strip comprised of two or more layers of insulating materials on a conductor backed dielectric substrate as shown in Figure 1a. Alternatively, a single layer strip may be used with a multi-layered dielectric substrate as shown in Figure 1b. The design guidelines presented in this paper are meant to optimize the dielectric thickness and permittivity t_1, t_2, and t_3 and ϵ_{r1}, ϵ_{r2}, and ϵ_{r3} respectively and the ridge width, 2a, so that the following design criteria are met:

1. Cutoff higher order modes
2. High field confinement in the ridge
3. Large field decay in y - direction
4. Low dispersion

Throughout this study, two assumptions are made. The first is $\epsilon_{r1} = \epsilon_{r3}$ which not only simplifies the design, but it also describes semiconductor LRDW fabricated using MBE [5] and silicon-insulator-silicon LRDW. The second assumption is that the design is for the LRDW shown in Figure 1a. The procedures for the LRDW shown in Figure 1b are similar with the only difference being a change in the effective dielectric constant for region II.

LRDW supports two fundamental modes; an E^y_{pq} mode that has a dominant y- directed electric field and an E^x_{pq} mode that has a dominant x- directed electric field where p and

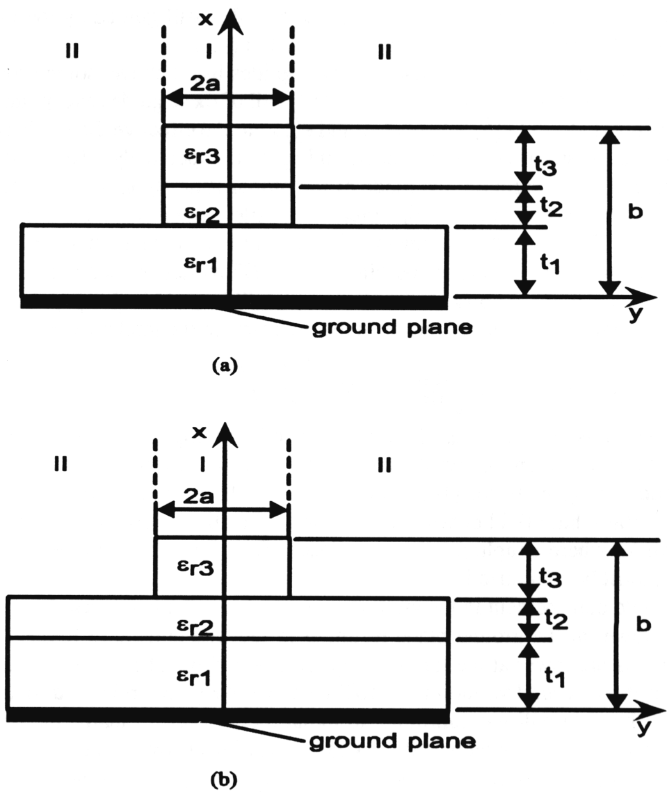

Figure 1: Layered ridge dielectric waveguide (a) consisting of a multilayered dielectric ridge on a conductor backed substrate (b) consisting of a single layered ridge on a multi-layered conductor backed substrate.

q indicate the order of the mode in the x and y directions respectively. The E^y mode is shorted out at low frequencies by the ground plane whereas the E^x_{11} mode has no cutoff frequency and is dominant at low frequencies. For E^x modes, the continuity of the electric flux density across the dielectric layers allows the electric field in the second layer to be given by $E_2 = (\epsilon_1/\epsilon_2)E_1 = (\epsilon_3/\epsilon_2)E_3$. Therefore by selecting the permittivity of the dielectric layers such that $\epsilon_2 < \epsilon_1, \epsilon_3$ and operating the guide over the frequency range where $(\beta/k_o)^2 < \epsilon_2$, the propagating signal is confined in the second layer or the "guiding layer." As the frequency increases, $(\beta/k_o)^2 > \epsilon_2$, the signal is still guided by the ridge but becomes confined in one of the two higher permittivity layers.

Since LRDW is similar to the other dielectric waveguides listed above, some aspects of its design are similar. Extending Oliner's analysis[13] , all of these guides except image guide will leak energy if $\epsilon^I_{eff} < \epsilon^{II}_{eff}$ where ϵ^I_{eff} and ϵ^{II}_{eff} are the effective dielectric constants of the strip and the substrate regions shown in Figure 1 respectively when they are analyzed independently. Furthermore, the mode of the propagating signal is not relevant since reflections at the sidewalls of the ridge create oppositely polarized modes in both regions I and II [13] . Therefore, if a dominant E^x mode is to be maintained, the LRDW must be designed to cutoff the E^y mode and higher order E^x modes in each region. Although this criteria leads to more conservative designs, it will be used in this paper.

High field confinement, the ratio of power in the dielectric to the total power:

$$R = \frac{\iint_{dielectric}[\mathrm{Re}(\mathbf{E} \times \mathbf{H}) \bullet \mathbf{z}]dS}{\iint_{all}[\mathrm{Re}(\mathbf{E} \times \mathbf{H}) \bullet \mathbf{z}]dS} \tag{1}$$

is required to reduce parasitic influences of the package and coupling to other waveguides. Furthermore, it has been shown that weak, lateral field confinement increases radiation loss from dielectric waveguide bends [14] . Therefore, $R > 0.5$ is often cited as a design criteria [6] . In addition, high field confinement in the y- direction is critical for antenna distribution networks where coupling between adjacent feed lines that may be several wavelengths long must be minimized.

Furthermore, field confinement in the guiding layer has several advantages. First, the magnetic field is lower at the ground plane resulting in reduced conductor losses [7] . In addition, the fields are lower at the top of the guide where fabrication defects induce radiation loss, and if the second variation of LRDW shown in Figure 1b is used, defects along the sides of the strip will not contribute to radiation loss[12] . Finally, the fields are similar to those of microstrip which facilitates easy transitions between microstrip and LRDW required for integration of active elements or microstrip patch antennas. Thus, besides maximizing the total field confinement R, the design should also maximize the ratio of the power in the guiding layer to the total power, R_G.

3. LRDW Design

The Effective Dielectric Constant (EDC) method first proposed by Knox and Toulios for image guide and insulated image guide [2] [7] and later generalized by McLevige [3] has proven useful for estimating the effective dielectric constant, ϵ_{eff}, and the magnitudes of the electromagnetic fields of several transmission lines and dielectric waveguides. In addition, it has been used in the design of transitions between LRDW and rectangular waveguide [10] and image guide couplers [2] [3] . It is therefore reasonable to use the EDC method in the design of LRDW with the waveguide initially partitioned into regions

I and II as shown in Figure 2 and later recombined as shown in Figure 3 as is normally done in the EDC method [3] [10] .

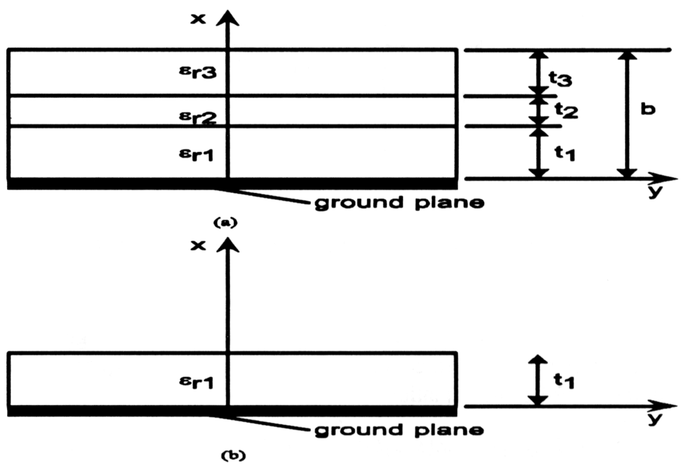

Figure 2: Layered ridge dielectric waveguide partitioned into (a) region I (b) region II.

Before proceeding, the power confinement ratio defined in Eqn. 1 is not easily applied in the EDC method since a full description of the fields for the dielectric waveguide are not determined. Therefore, two new power confinement ratios:

$$R_x = \frac{\int_0^b \mathrm{Re}[E_x(x)H_y^*(x)]dx}{\int_0^\infty \mathrm{Re}[E_x(x)H_y^*(x)]dx} \tag{2}$$

$$R_y = \frac{\int_0^a \mathrm{Re}[E_x(y)H_y^*(y)]dy}{\int_0^\infty \mathrm{Re}[E_x(y)H_y^*(y)]dy} \tag{3}$$

are defined for Figures 2 and 3 respectively. Since the product of R_x and R_y is approximately equal to R, the design criteria of $R > 0.5$ is replaced by $R_xR_y > 0.5$. Similarly, the ratio of the power in the guiding layer to the total power is defined from Figure 2a to be:

$$R_G = \frac{\int_{t_1}^{t_1+t_2} \mathrm{Re}[E_x(x)H_y^*(x)]dx}{\int_0^\infty \mathrm{Re}[E_x(x)H_y^*(x)]dx} \tag{4}$$

An appropriate starting point in the design process is to determine the maximum ridge thickness, b, for a specific upper frequency limit. At low frequencies, a conductor backed dielectric slab supports a single mode with an electric field component normal to the ground plane. As the frequency increases, higher order modes may propagate, the first of which has an electric field component in the plane of the dielectric slab. The cutoff frequency for this E^y mode is dependent on the dielectric thickness and permittivity by

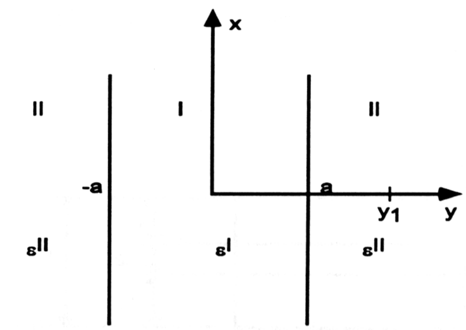

Figure 3: Layered ridge dielectric waveguide as modelled in the effective dielectric constant method.

the simple relationship $f_c = c/4b\sqrt{\epsilon_r - 1}$ [1] where c is the velocity of light. For the dielectric ridge structure comprised of three dielectric slabs, the cutoff frequency must be determined by solving the following equation:

$$0 = \cot(k_{xc1}t_1) - K\tan(k_{xc2}t_2) - \tan(k_{xc3}t_3)\left\{\frac{1}{K}\cot(k_{xc1}t_1)\tan(k_{xc2}t_2) + 1\right\} \quad (5)$$

where $k_{xci} = k_c\sqrt{\epsilon_{ri} - 1}$, $k_{xc1} = k_{xc3}$ since $\epsilon_{r1} = \epsilon_{r3}$, $k_c = 2\pi f_c\sqrt{\epsilon_o\mu_o}$, and:

$$K = \sqrt{\frac{\epsilon_{r2} - 1}{\epsilon_{r1} - 1}} \quad (6)$$

All of the $k_{xci}t_i$ terms can be related to b by introducing normalized thicknesses:

$$Q = \frac{t_1}{b} \quad (7)$$

$$X = \frac{t_2}{b - t_1} = \frac{t_2}{b(1 - Q)} \quad (8)$$

and since $t_1 + t_2 + t_3 = b$, $t_3 = b(1 - Q)(1 - X)$. The $k_{xci}t_i$ terms are now:

$$k_{xc1}t_1 = V_cQ \quad (9)$$

$$k_{xc2}t_2 = V_cX(1 - Q)K \quad (10)$$

$$k_{xc3}t_3 = V_c(1 - X)(1 - Q) \quad (11)$$

where:

$$V_c = b\frac{2\pi f_c}{c}\sqrt{\epsilon_{r1} - 1} \quad (12)$$

is similar to the normalized cutoff frequency used for image guide [2] .

For a given dielectric waveguide, it is desirable to operate at or near the cutoff frequency [6] which is equivalent to operating at V_c, and for a given dielectric ridge thickness, the cutoff frequency should be maximized. Thus, the design of the LRDW should maximize V_c. Upon solving Eqn. 5 for V_c, the value of Q that yields the maximum V_c, $Q_{\max}$, as a function of K and X can be determined, and using these values of $Q_{\max}$, $V_{c\max}$ as a function of K and X can be found. Both of these are plotted in Figures 4 and

5 respectively where it is seen that $V_{c\,\max}$ of LRDW is significantly greater than $V_{c\,\max}$ of image guide and millimeter-wave dielectric ridge guide (K=1). Furthermore,

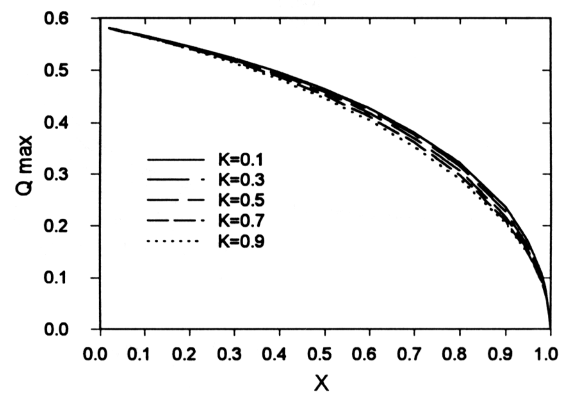

Figure 4: Value of Q that results in the maximum normalized cutoff frequency, $V_{c\,\max}$, in the ridge region as a function of X and K.

if the permittivity of the guiding layer is decreased, K decreased, or the thickness of the guiding layer increased, X increased, $V_{c\,\max}$ increases. As a result, the LRDW should be designed with a large X and small K to maximize the cutoff frequency. These conditions also result in a small $Q_{\max}$ and a larger ridge thickness for a specific cutoff frequency. To design LRDW for a broad range of X and K, the following equations derived from Figures 4 and 5 may be used:

$$Q_{\max}(V_c = V_{c\,\max}) = \frac{0.5864 - 0.7085X - 0.0285X^2 + 0.1532X^3 - 0.0038K}{1 - 0.9398X + 0.0058K} \tag{13}$$

$$V_{c\,\max}(Q = Q_{\max}) = \frac{1.5718 - 0.7254X - 1.4175K - 0.2999X^2 + 0.3921K^2 + 0.9601XK}{1 - 0.7283X - 0.8981K - 0.1946X^2 + 0.2460K^2 + 0.8799XK} \tag{14}$$

Since the $Q_{\max}$ and $V_{c\,\max}$ have been determined, the best choice for X, ϵ_{r1}, and K now needs to be found. First, the optimum value of X will be determined. Using the EDC method to determine ϵ^I, ϵ^{II}, and the fields E_x and H_y for the ridge structures shown in Figure 2 with $Q = Q_{\max}$, the field confinement ratios R_x and R_G and $\Delta\epsilon = \epsilon^I - \epsilon^{II}$ which is critical in determining R_y can be found. Figures 6, 7, and 8 show these design criteria as a function of X, and although $\Delta\epsilon$, R_x, and R_G are also dependent on K and ϵ_{r1}, the general observations are not. To illustrate the results, a higher order mode cutoff frequency of 42 GHz was assumed in the determination of $f_c * b$ and is shown on the curves along with a set of points at 32 GHz. From the criteria of maximizing R_x and R_G over a broad frequency bandwidth, X should be as large as possible. The parameter $\Delta\epsilon$ should be large to maximize R_y which indicates the need to choose a small value of X, however $\Delta\epsilon$ is more frequency dependant for small X. Furthermore, $\Delta\epsilon$ is large only at

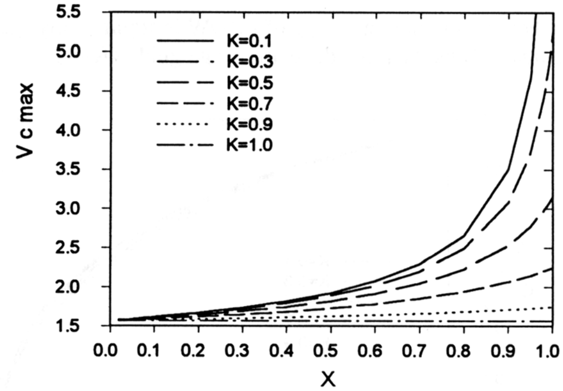

Figure 5: Maximum normalized cutoff frequency, $V_{c\,\mathbf{max}}$, as a function of X and K when $Q = Q_{\mathbf{max}}$.

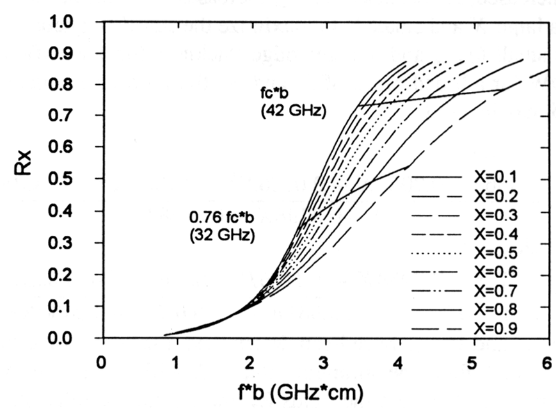

Figure 6: Field confinement factor, R_x, as a function of normalized frequency, $f * b$, and X for $K = 0.5$, $Q = Q_{\mathbf{max}}$, and $\epsilon_{r1} = 6.0$.

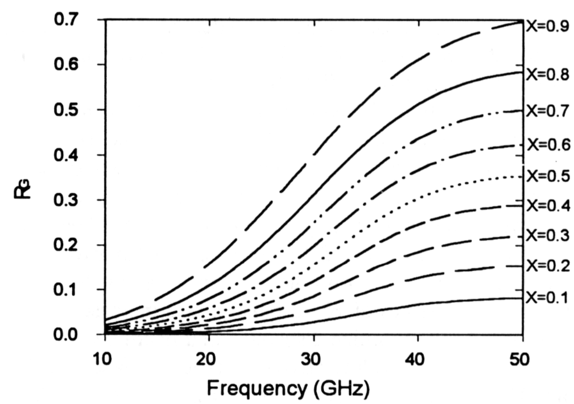

Figure 7: Ratio of power in the guiding layer to total power, R_G, as a function of frequency and X for $K = 0.5$, $Q = Q_{\max}$, and $\epsilon_{r1} = 6.0$.

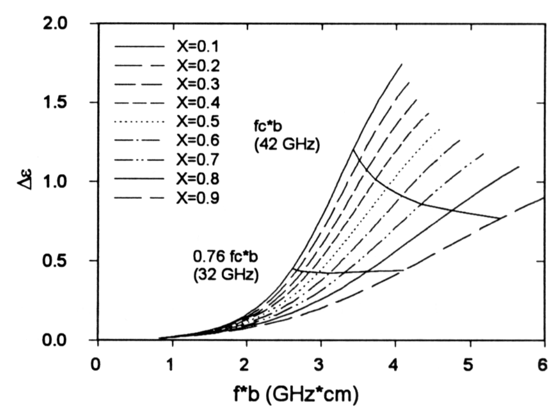

Figure 8: $\Delta\epsilon = \epsilon^I - \epsilon^{II}$ as a function of normalized frequency, $f * b$, and X for $K = 0.5$, $Q = Q_{\max}$, and $\epsilon_{r1} = 6.0$.

$V_{c\max}$, while at lower frequencies, it is less dependent on X. Thus, an appropriate choice for X is 0.8. Note that larger values of X ($X \approx 1$) changes the dielectric waveguide from LRDW to a form of millimeter-wave dielectric ridge guide.

By analyzing LRDW with the known parameters $X = 0.8$ and $Q = Q_{\max}$, K and ϵ_{r1} can be determined to optimize the design. Figures 9, 10, and 11 show R_x, R_G, and $\Delta\epsilon$ respectively as a function of frequency, K, and ϵ_{r1}. Also shown on the figures is the locus of points at a cutoff frequency of 42 GHz and a lower frequency of 32 GHz, or in more general term, a normalized frequency of $f_c * b$ and $0.76 f_c * b$. Maximum R_x occurs when $K \approx 0.5$ at the higher order mode cutoff frequency and 0.3 at lower frequencies, whereas R_G is maximum when $K \approx 0.3$ across the frequency bandwidth if $\epsilon_{r1} > 4$. Although $\Delta\epsilon$ is maximum for larger values of K, dispersion also increases as K increases. Thus, a good value of K is 0.4. To minimize dispersion and maximize R_x and R_G, a small ϵ_{r1} is desired. However, materials with relative dielectric constants smaller than 2.0 are not widely available. Therefore, if $K = 0.4$ and $\epsilon_{r2} = 2.0$ are used in Eqn. 6, the minimum practical ϵ_{r1} is found to be 7.0 which reduces the bandwidth. Before proceeding, notice that dispersion is greater and R_x is smaller if $K = 1$ which is the condition required for image guide and millimeter-wave dielectric ridge waveguide.

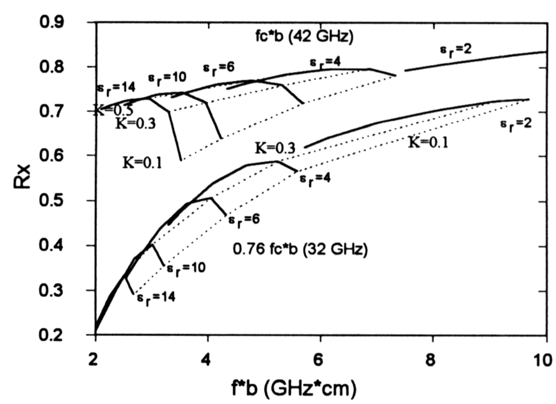

Figure 9: Field confinement factor, R_x, as a function of normalized frequency, $f * b$, K, and ϵ_{r1} for LRDW with $Q = Q_{\max}$ and $X = 0.8$. (constant permittivity in solid lines, constant K in dotted lines)

At this point, the optimum values of Q, X, and K are known. Continuing with the EDC method of analysis in an effort to determine the ridge width a and to relate it to the parameters found above, consider the structure shown in Figure 3. Assuming E_x and H_y fields with a magnetic wall at $y = 0$, the eigenvalue equation required to determine ϵ_{eff} is:

$$(k_{y1}a)\tan(k_{y1}a) - ha = 0 \tag{15}$$

where:

$$k_{y1}a = k_o a\sqrt{\epsilon^I - \epsilon_{eff}} \tag{16}$$

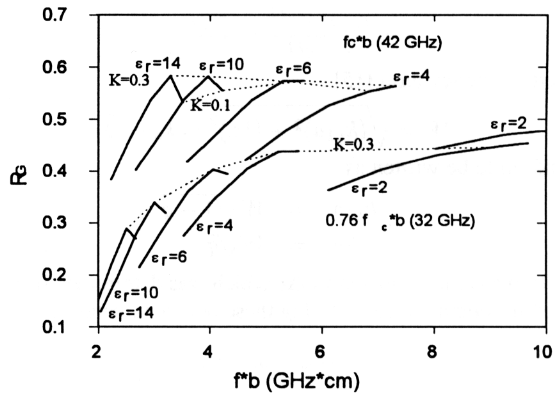

Figure 10: Ratio of power in the guiding layer to total power, R_G, as a function of normalized frequency, $f * b$, K, and ϵ_{r1} for $Q = Q_{\max}$ and $X = 0.8$. (constant permittivity in solid lines, constant K in dotted lines.)

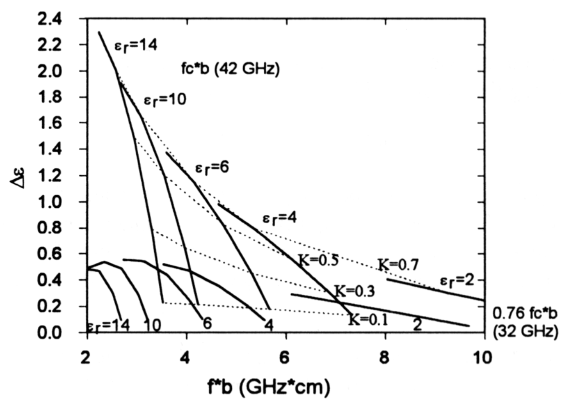

Figure 11: $\Delta\epsilon = \epsilon^I - \epsilon^{II}$ as a function of normalized frequency, $f * b$, K, and ϵ_{r1} for $Q = Q_{\max}$ and $X = 0.8$. (constant permittivity in solid lines, constant K in dotted lines.)

$$ha = k_o a\sqrt{\epsilon_{eff} - \epsilon^{II}} \tag{17}$$

Defining a filling factor of [15] :

$$q = \frac{\epsilon_{eff} - \epsilon^{II}}{\epsilon^{I} - \epsilon^{II}} = \frac{\epsilon_{eff} - \epsilon^{II}}{\Delta\epsilon} \tag{18}$$

and a normalized frequency term [15] :

$$W = \sqrt{(k_{y1}a)^2 + (ha)^2} = k_o a\sqrt{\Delta\epsilon} \tag{19}$$

permits $k_{y1}a$ and ha to be written as:

$$k_{y1}a = W\sqrt{1-q} \tag{20}$$

$$ha = W\sqrt{q} \tag{21}$$

Thus, all of the terms are now related to $\Delta\epsilon$ which was determined in Figure 11 and ϵ_{eff} which is required for circuit designs. Using these new parameters, Eqn. 15 results in:

$$W = \frac{1}{\sqrt{1-q}}\tan^{-1}\sqrt{\frac{q}{1-q}} \tag{22}$$

Unfortunately, in a typical design, W is known and q needs to be found. Although Eqn. 22 cannot be inverted directly, a simple expression for q has been found:

$$q = \frac{0.97487}{1 + (\frac{W}{1.0816})^{-1.83984}} \tag{23}$$

which is accurate for $W < \pi$. Note that this equation is general and can be used to find the effective dielectric constant of dielectric slab waveguide without solving transcendental equations as is normally done. From the eigenvalue equation for the E^x and E^y modes, it is found that the cutoff frequency is given by $W = n\pi/2$ which results in a maximum filling factor of 0.646 and a maximum value of a of:

$$a_{\max} = \frac{c}{4f_c\sqrt{\Delta\epsilon}} \tag{24}$$

At this point, no knowledge of the power confinement parameters in the y- direction exists. Determining the fields for Figure 3 and using Eqn. 3, R_y can be found to be:

$$R_y = \frac{\sin^2 B + B\tan B}{1 + B\tan B} \tag{25}$$

where $B = W\sqrt{1-q}$. The maximum R_y is found at the cutoff frequency to be 0.844. Although R_y is a useful design criteria, it is not easily related to circuit designs. A more useful design criteria is the ratio of the power at some distance from the center of the waveguide to the power at the center, $D = P(y = y_1)/P(y = 0)$, which is found to be:

$$D = \cos^2(B)e^{-2B(n-1)\tan B} \tag{26}$$

where $n = y_1/a$. A typical design requirement is to determine the value of y_1 or n for a specific value of D. This relationship is found from Eqn. 26 to be:

$$n = 1 - \frac{\ln\frac{D}{\cos^2 B}}{2B\tan B} \tag{27}$$

Note that q, R_y, and D are all a function of W which is shown in Figure 12.

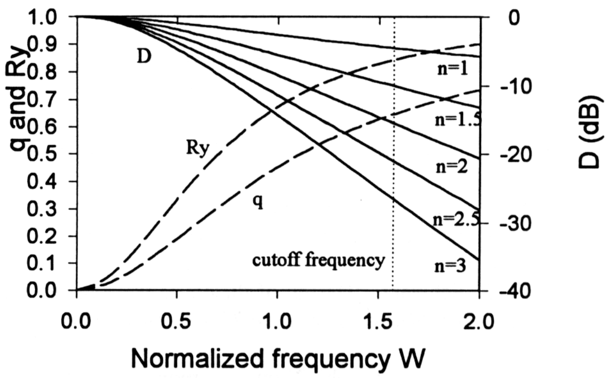

Figure 12: Field confinement terms in the y-direction, D and R_y, and the filling factor q as a function of the normalized frequency $W = k_o a\sqrt{\Delta\epsilon}$.

4. Design Results

To review the optimum design for LRDW, it has been shown that $X = 0.8$ and $K = 0.4$ are the preferred values. Using these parameters in Eqns. 13 and 14 results in $Q = Q_{\max} = 0.3125$ and $V_{c\max} = 2.367$. Thus, if the upper frequency and ϵ_{r1} are specified, b can be found from Eqn. 12. Then, either by using the EDC method and determining $\Delta\epsilon$ or reading it from Figure 11, a can be determined from Eqn. 24. The effective dielectric constant, ϵ_{eff}, can be determined by finding q from Eqn. 23 or Figure 12 and Eqn. 18. Finally, the power confinement and dispersion can be obtained from Figures 9-12. An alternative design procedure is to start with the upper frequency and a required power decay in the y- direction to minimize coupling to other lines. Using Figure 12, a and $\Delta\epsilon$ can be determined, and then the required ϵ_{r1} can be found from Figure 11. Finally, the dielectric thicknesses and the permittivity of the guiding layer can be determined from the optimum values of Q, X, K, and $V_{c\max}$. If this design procedure is followed, the ratio of a/b is found to be approximately twice the optimum value of one found for image guide [6] .

5. Conclusions

A set of design procedures consisting of closed form equations and design graphs for layered ridge dielectric waveguide has been developed. The design is conservative in that it places strict requirements on the cutoff frequency of higher order modes. Thus, since some of these modes are weakly excited by the LRDW, it may be possible to operate the waveguide above the upper frequency specified in this design. Throughout the paper, comparisons to image guide have been made. Lastly, several new closed form equations which are useful for dielectric waveguide design in general have been presented.

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