Attenuation in Rectangular Waveguides with Finite Conductivity Walls

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Abstract. *We present a fundamental and accurate approach to compute the attenuation of electromagnetic waves propagating in rectangular waveguides with finite conductivity walls. The wavenumbers k_x and k_y in the x and y directions respectively, are obtained as roots of a set of transcendental equations derived by matching the tangential component of the electric field (E) and the magnetic field (H) at the surface of the waveguide walls. The electrical properties of the wall material are determined by the complex permittivity ε, permeability μ, and conductivity σ. We have examined the validity of our model by carrying out measurements on the loss arising from the fundamental TE_{10} mode near the cutoff frequency. We also found good agreement between our results and those obtained by others including Papadopoulos' perturbation method across a wide range of frequencies, in particular in the vicinity of cutoff. In the presence of degenerate modes however, our method gives higher losses, which we attribute to the coupling between modes as a result of dispersion.*

Keywords

Attenuation, rectangular waveguides, finite conductivity, electrical properties.

1. Introduction

Propagation of electromagnetic waves in circular waveguides has been widely investigated, for waveguides with lossy [1] and superconducting walls [2], [3], unbounded dielectric rod [4], bounded dielectric rod in a waveguide [5], and multilayered coated circular waveguide [6]. The computations given by these authors were based on a method suggested by Stratton [7]. The circular symmetry of the waveguide allows the boundary matching equations to be expressed in a single variable which is the radial distance *r*. The eigenmodes could therefore be obtained from a single transcendental equation. This approach cannot be implemented in the case of rectangular symmetry where a 2D Cartesian coordinate system must be used.

Rectangular waveguides are employed extensively in microwave and millimeter wave receiver [8] ,[9], [10] since they are much easier to manipulate than circular waveguides (bend, twist) and also offer significantly lower cross polarization component. Despite that, not much has recently been published on analyzing the guided propagation of electromagnetic signals in lossy or superconducting rectangular waveguides.

The approximate power-loss method has been widely used in analyzing wave attenuation in lossy rectangular waveguides as a result of its simplicity and because it gives reasonably accurate result, when the frequency of the signal is well above cutoff [7], [11], [12], [13]. In this method, the field expressions are derived assuming perfectly conducting walls, allowing the solution to be separated into TE and TM modes. To calculate the attenuation, ohmic losses are assumed to exist due to small field penetration into the conductor walls. The power-loss method however fails near cutoff, as the attenuation obtained using this method diverges to infinity when the signal frequency f approaches the cutoff frequency f_c.

Bladel [14], and Robson [15] discussed degenerate modes propagation in lossy rectangular waveguides, but neither was able to compute the attenuation values accurately near cutoff. Like the power-loss method, their theories predict infinite attenuation at cutoff. An expression valid at all frequencies is given by Kohler and Bayer [16] and reiterated by Somlo and Hunter in [17]. This expression however is only applicable to the TE_{10} dominant mode.

The perturbation solution developed by Papadopoulos [18] shows that the propagation of a mode does not merely stop at f_c. Rather, as the frequency approaches f_c, transition from a propagating mode to a highly attenuated mode takes place. The propagation of waves will only cease when $f = 0$. Papadopoulos' perturbation method (PPM) shows that the attenuation at frequencies well above f_c remains in close agreement with that computed using the power loss method for non-degenerate modes. Because of this reason, PPM is perceived as a more accurate technique in computing the loss of waves traveling in waveguides. A similar solution has been derived by Gustincic using the variational approach in [12], [19].

In [20], we have introduced a novel accurate technique to compute the propagation constant of waves in rectangular walls with finite conductivity. The method has been applied to investigate the attenuation of the dominant mode. In this paper, we shall develop further the method in [20] to show the presence of mode coupling effects in degenerate modes. Here, in order to present a complete scheme, we outline the derivation of the transcendental equation in [20] for convenience. In our method, the solution for the attenuation constant is found by solving two transcendental equations derived from matching the tangential components of the electromagnetic field at the waveguide walls and making use of the surface impedance concept. The attenuation constants for the dominant non-degenerate TE_{10} mode and the degenerate TE_{11} and TM_{11} modes are computed and compared with the power-loss method and the PPM. We will demonstrate that our method gives more realistic values for the degenerate modes since the formulation allows co-existence and exchange of power between these modes while other methods treat each one independently.

Finally, we would like to emphasize that significant deviation between the power loss and rigorous methods computations start to appear at frequencies well below cutoff where waveguides are used as filters and for other applications. At frequencies immediately below cutoff, the attenuation diverges at very high rate that at some stage power transmission in the waveguide becomes negligible. At these frequencies (very close to cutoff) the deviation in the computed results between our method and the power loss results is substantial. Experimentally measured attenuation confirms the integrity of our computation close to cutoff.

2. Formulation

2.1 Fields in Rectangular Waveguides

In a lossless waveguide, the boundary condition requires that the resultant tangential electric field E_t and the normal derivative of the tangential magnetic field $\partial H_t/\partial a_n$ to vanish at the waveguide wall, where a_n is the normal direction to the waveguide wall. Due to the finite conductivity of the waveguide material, both E_t and $\partial H_t/\partial a_n$ are not exactly zero at the boundary. To account for the presence of fields inside the walls, we have introduced two phase parameters; ϕ_x and ϕ_y, which we shall refer to as the field's penetration factors in the x and y directions, respectively.

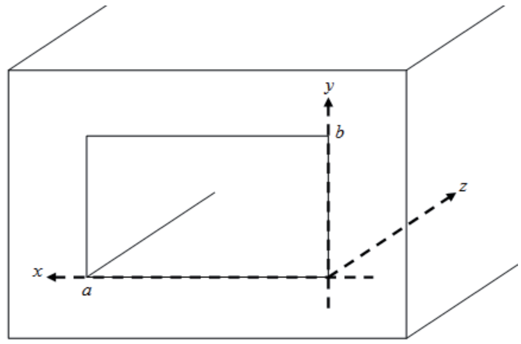

Fig. 1. A rectangular waveguide.

For waves propagating in a lossy rectangular waveguide, as shown in Fig. 1, a superposition of TM and TE waves is necessary to satisfy the boundary condition at the wall [3], [7]. The longitudinal electric and magnetic field components E_z and H_z, respectively, can be derived by solving Helmholtz homogeneous equation in Cartesian coordinate. Using the method of separation of variables [13], we obtain the following set of field equations:

$$E_z = E_0 \sin(k_x x + \phi_x)\sin(k_y y + \phi_y), \tag{1}$$

$$H_z = H_0 \cos(k_x x + \phi_x)\cos(k_y y + \phi_y) \tag{2}$$

where E_0 and H_0 are constant amplitudes of the fields and k_x and k_y are the wavenumbers in the x and y directions, respectively. A wave factor of form $\exp[j(\omega t - k_z z)]$ is assumed but is omitted from the equations for simplicity. Here, $\omega = 2\pi f$ is the angular frequency and k_z is the propagation constant. k_z for each mode will be found by solving for k_x and k_y and substituting the results into the dispersion relation:

$$k_z = \sqrt{k_0{}^2 - k_x{}^2 - k_y{}^2}\ . \tag{3}$$

Here, k_0 is the wavenumber in free space. k_x, k_y, and k_z are complex and may be written as:

$$k_x = \beta_x - j\alpha_x\,, \tag{4}$$

$$k_y = \beta_y - j\alpha_y\,, \tag{5}$$

$$k_z = \beta_z - j\alpha_z \tag{6}$$

where β_x, β_y and β_z are the phase constants and α_x, α_y and α_z are the attenuation constants in the x, y, and z directions, respectively.

Equations (1) and (2) must also apply to a perfect conductor waveguide. In that case E_z and $\partial H_z/\partial a_n$ are either at their maximum magnitude or zero at both $x = a/2$ and $y = b/2$, therefore:

$$\sin\left(\frac{k_x a}{2} + \phi_x\right) = \sin\left(\frac{k_y b}{2} + \phi_y\right) = \pm 1 \text{ or } 0\,. \tag{7}$$

Solving (7), we obtain,

$$\phi_x = \frac{(m\pi - k_x a)}{2}\,, \tag{8}$$

$$\phi_y = \frac{(n\pi - k_y b)}{2} \tag{9}$$

where the integers m and n denote the number of half cycle variations in the x and y directions, respectively and every combination of m and n defines a possible TE_{mn} and TM_{mn} modes. For waveguides with perfectly conducting wall, $k_x = m\pi/a$ and $k_y = n\pi/b$, (8) and (9) result in zero penetration and E_z and H_z in (1) and (2) are reduced to the fields of a lossless waveguide. To take the finite conductivity into account we allow k_x and k_y to take complex values yielding non-zero penetration of the fields into the waveguide material. This in turn results in complex value for the propagation constant of the waveguide k_z (see (3)) which yields loss in propagation.

Substituting (1) and (2) into Maxwell's source-free curl equations and expressing the transverse field components in terms of E_z and H_z [13], we obtain:

$$H_x = \frac{j}{h^2}\left[k_z k_x H_0 + \omega\varepsilon_0 k_y E_0\right]\sin(k_x x + \phi_x)\cos(k_y y + \phi_y) \tag{10}$$

$$H_y = \frac{j}{h^2}\left[k_z k_y H_0 - \omega\varepsilon_0 k_x E_0\right]\cos(k_x x + \phi_x)\sin(k_y y + \phi_y) \tag{11}$$

$$E_x = -\frac{j}{h^2}\left[k_z k_x E_0 - \omega\mu_0 k_y H_0\right]\cos(k_x x + \phi_x)\sin(k_y y + \phi_y) \tag{12}$$

$$E_y = -\frac{j}{h^2}\left[k_z k_y E_0 + \omega\mu_0 k_x H_0\right]\sin(k_x x + \phi_x)\cos(k_y y + \phi_y) \tag{13}$$

where μ_0 and ε_0 are the permeability and permittivity of free space, respectively, and $h^2 = k_x^2 + k_y^2$. These expressions show that the field is a superposition of TE and TM modes.

2.2 Constitutive Relations for TE and TM Modes

Using Maxwell equations it can be shown that the ratio of the tangential component of the electric field to the surface current density at the conductor surface is given by [21]

$$\frac{E_t}{H_t} = \sqrt{\frac{\mu}{\varepsilon}} \tag{14}$$

where μ and ε are the permeability and permittivity of the wall material, respectively, and $\sqrt{\mu/\varepsilon}$ is the intrinsic impedance of the wall material. The subscript t in (14) denotes tangential fields. The dielectric constant is complex and ε may be written as

$$\varepsilon = \varepsilon_0 - j\frac{\sigma}{\omega} \tag{15}$$

where σ is the conductivity of the wall.

At the surface of the waveguide in the x-direction at $y = b$, $E_z/H_x = -E_x/H_z = \sqrt{\mu/\varepsilon}$. Substituting (1), (2), (10), and (12) into (14), we obtain:

$$\frac{-E_x}{H_z} = \frac{j}{h^2}\left(\frac{E_0}{H_0}k_z k_x - \omega\mu_0 k_y\right)\tan(k_y b + \phi_y) = \sqrt{\frac{\mu}{\varepsilon}}, \tag{16a}$$

$$\frac{H_x}{E_z} = \frac{j}{h^2}\left(\frac{H_0}{E_0}k_z k_x + \omega\varepsilon_0 k_y\right)\cot(k_y b + \phi_y) = \sqrt{\frac{\varepsilon}{\mu}}. \tag{16b}$$

Similarly, at the surface in the y-direction, $x = a$, we obtain $E_y/H_z = -E_z/H_y = \sqrt{\mu/\varepsilon}$. Substituting (1), (2), (11), and (13) into (14), we obtain:

$$\frac{E_y}{H_z} = \frac{-j}{h^2}\left(\frac{E_0}{H_0}k_z k_y + \omega\mu_0 k_x\right)\tan(k_x a + \phi_x) = \sqrt{\frac{\mu}{\varepsilon}}, \tag{17a}$$

$$\frac{-H_y}{E_z} = \frac{-j}{h^2}\left(\frac{H_0}{E_0}k_z k_y - \omega\varepsilon_0 k_x\right)\cot(k_x a + \phi_x) = \sqrt{\frac{\varepsilon}{\mu}}. \tag{17b}$$

By letting the determinant of the coefficients of E_0 and H_0 in (16) and (17) vanish we obtain the transcendental equations:

$$\left[\frac{j\omega\mu_0 k_y \tan(k_y b + \phi_y)}{h^2} + \sqrt{\frac{\mu}{\varepsilon}}\right]\left[\frac{j\omega\varepsilon_0 k_y \cot(k_y b + \phi_y)}{h^2} - \sqrt{\frac{\varepsilon}{\mu}}\right] = \left[\frac{k_z k_x}{h^2}\right]^2, \tag{18a}$$

$$\left[\frac{j\omega\mu_0 k_x \tan(k_x a + \phi_x)}{h^2} + \sqrt{\frac{\mu}{\varepsilon}}\right]\left[\frac{j\omega\varepsilon_0 k_x \cot(k_x a + \phi_x)}{h^2} - \sqrt{\frac{\varepsilon}{\mu}}\right] = \left[\frac{k_z k_y}{h^2}\right]^2. \tag{18b}$$

In the above equations, k_x and k_y are the unknowns and k_z can then be obtained from (3). A multi-variable root searching algorithm such as the Powell Hybrid root-searching algorithm in a NAG routine [22] can be used to find the roots of k_x and k_y. The routine requires initial guesses of k_x and k_y for the search. For good conductors, suitable guess values are clearly those close to the perfect conductor values. For TE_{10} mode, m and n are set to 1 and 0, respectively, hence the search starts with $k_x = \pi/a$ and $k_y = 0$. For TE_{11} and TM_{11} modes, m and n are both set to 1 and the initial guess values are π/a and π/b respectively for both modes. It is worthwhile noting that when a search is started with exactly these values, the solution did not always converge to the required mode. It was often necessary to refine the initial values slightly in order to ensure convergence to the correct mode.

3. Results and Discussion

To validate the results experimentally, we measured the loss as a function of frequency for a 20 cm long rectangular waveguide using an Anritsu 37369C Vector Network Analyzer (VNA). The VNA was calibrated using the Thru-

Reflect-Line (TRL) method. The waveguide was made of copper and had dimensions of $a = 1.30$ cm and $b = 0.64$ cm. The loss was observed from the S_{21} parameter of the scattering matrix. The measurement was performed in the frequency range where only TE_{10} mode could propagate, while other higher order modes are evanescent.

We compared the attenuation of the TE_{10} mode below cutoff as predicted by our method, the conventional power-loss method, and the PPM as shown in Fig. 2. As can clearly be seen, the attenuation constant α_z computed from the power-loss method diverges sharply to infinity, as the frequency approaches f_c, and is very different to the measured results, which show clearly that the loss at frequencies below f_c is high but finite. The attenuation curves computed using our method and the PPM in Fig. 2 match very well and in fact are indistinguishable on the plot. The figures for the loss between 11.47025 GHz and 11.49950 GHz computed by the two methods agree with measurement to within 5% which is comparable to the error in the measurement.

Fig. 3 shows the attenuation curve when the frequency is extended to higher values. Here, the loss due to TE_{10} alone could no longer be measured as higher-order modes, such as TE_{11} and TM_{11}, etc., start to propagate. At higher frequencies the loss due to TE_{10} predicted by the three methods, i.e. our method, the power-loss method, and the PPM are in very close agreement.

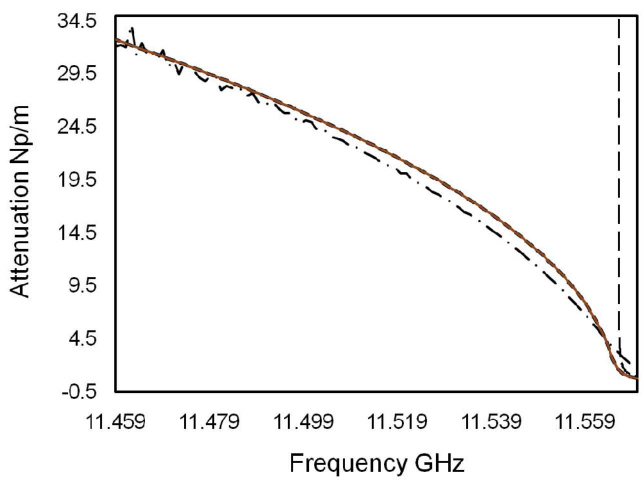

Fig. 2. Loss of TE_{10} mode in a hollow rectangular waveguide below cutoff. ——— our method, — — — — — the power-loss method, ▪▪▪▪▪▪▪▪▪▪▪▪▪ the Papadopoulos' Perturbation method, and — · — · — · the measurement result.

Next, we compared the propagation constants k_z of TE_{11} and TM_{11} degenerate modes, which have equal phase constants β_z in the lossless case. Here the power-loss method can only give α_z whereas both the PPM and our method give both β_z and α_z. Fig. 4 shows that the phase constant β_z for TE_{11} mode computed using our method is in good agreement with that computed using the PPM. For TM_{11} mode however, the results differ slightly. Unlike that of the lossless case, the values of β_z differ slightly for the different modes in a lossy waveguides due to dispersive effects.

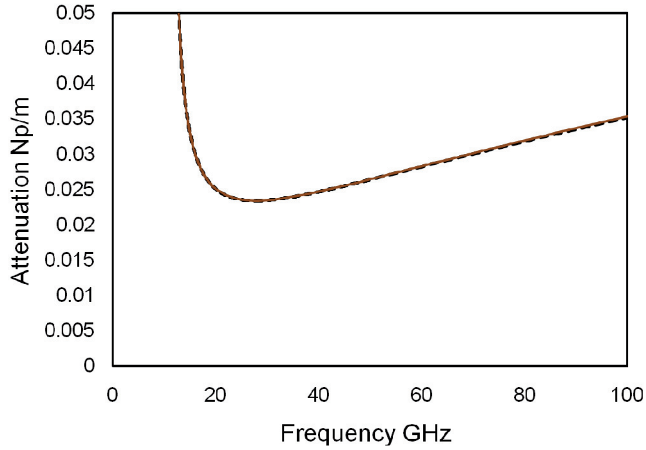

Fig. 3. Loss of TE_{10} mode in a hollow rectangular waveguide below cutoff. ——— our method, — — — — — the power-loss method, ▪▪▪▪▪▪▪▪▪▪▪▪▪ the Papadopoulos' Perturbation method.

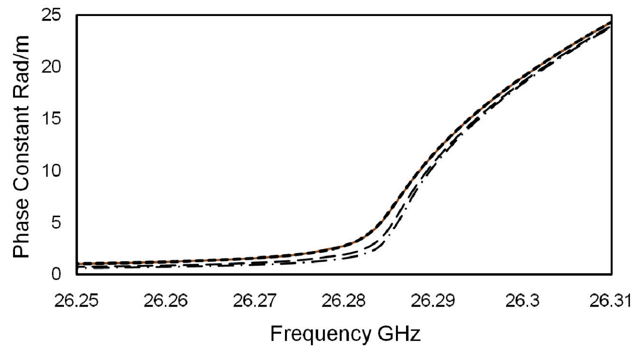

Fig. 4. Phase constant β_z of TE_{11} and TM_{11} in a rectangular waveguide. ▪▪▪▪▪▪▪▪▪▪▪ and ——— indicate β_z of TE_{11} computed using the PPM and our method, respectively. — · — · — and — — — indicate β_z of TM_{11} computed using the PPM and our method, respectively.

The behavior of the degenerate TE_{11} and TM_{11} modes is illustrated in Fig. 5 to Fig. 8, both near cutoff and in the propagating region. In Fig. 5 and Fig. 6, α_z computed by the PPM and our method, agree very well near cutoff. However, Fig. 7 and Fig. 8 show that when the frequency increases beyond 28.5 GHz for TE_{11} and 27.0 GHz for TM_{11}, the results start to disagree significantly.

To explain this disagreement we recall that power losses of a number of modes that propagate simultaneously in a waveguide is not simply additive [23]. The cross product terms between the different modes gives rise to additional dissipation, making the total loss greater than the one obtained from the addition of loss in independent propagation of single modes. This is because the product of the average power density, $P_{av} = ½\, Re(\mathbf{E_1} \times \mathbf{H_2}^*)$ of the electric field of mode 1 $\mathbf{E_1}$ and magnetic field of mode 2 $\mathbf{H_2}$, when integrated along the boundary, is not zero and the current induced by $\mathbf{H}_2$ will deliver power to mode 1, and vice versa. In this case, there will be coupling of power between multiple propagating modes, which give rise to power loss as a result of the change in the amplitude distribution of the fields across the area of the waveguide [23]:

$$\begin{aligned}
P_L &= \frac{1}{2}R \\
&\left\{\sum_{m=1}^{M}\sum_{n=1}^{M} A_m^{(TE)} A_n^{(TE)^*} \oint_c \left[H_{mc}^{(TE)} H_{nc}^{(TE)^*} + H_{mz}^{(TE)} H_{nz}^{(TE)^*}\right] dc \int_0^l \exp\left[j(\beta_m^{(TE)} - \beta_n^{(TE)})z\right] dz\right. \\
&+ \sum_{m'=1}^{M'}\sum_{n=1}^{M} A_{m'}^{(TM)} A_n^{(TE)^*} \oint_c \left[H_{m'c}^{(TM)} H_{nc}^{(TE)^*}\right] dc \int_0^\theta \exp\left[j(\beta_{m'}^{(TM)} - \beta_n^{(TE)})z\right] dz \\
&+ \sum_{m=1}^{M}\sum_{n'=1}^{M'} A_m^{(TE)} A_{n'}^{(TM)^*} \oint_c \left[H_{mc}^{(TE)} H_{n'c}^{(TM)^*}\right] dc \int_0^\theta \exp\left[j(\beta_m^{(TE)} - \beta_{n'}^{(TM)})z\right] dz \\
&\left.+ \sum_{m'=1}^{M'}\sum_{n'=1}^{M'} A_{m'}^{(TM)} A_{n'}^{(TM)^*} \oint_c \left[H_{m'c}^{(TM)} H_{n'c}^{(TM)^*}\right] dc \int_0^\theta \exp\left[j(\beta_{m'}^{(TM)} - \beta_{n'}^{(TM)})z\right] dz\right\}.
\end{aligned} \tag{19}$$

Here, $A^{(TE)}$ and $A^{(TM)}$ are arbitrary amplitude coefficients for the TE and TM modes respectively, R is the surface resistance, c is the contour around the inner surface of the waveguide, which is also normal to the propagating z axis. The subscript c represents the component of the transverse field tangential to the contour c. M is the number of different TE propagating modes, and M' is the number of different TM propagating modes.

It turns out that mode coupling increases the interaction between the propagating power and the waveguide walls, making the attenuation dependent on the axial distance from the source. Integrating the exponential terms in (19), the factor that determines coupling between modes can be written as [23]:

$$F = \frac{\exp[j(\beta_m^{TE} - \beta_n^{TM})l] - 1}{[j(\beta_m^{TE} - \beta_n^{TM})l]} \tag{20}$$

where β_m and β_n are the phase constants of 2 different modes which could be either TM or TE, while l is the length of the waveguide.

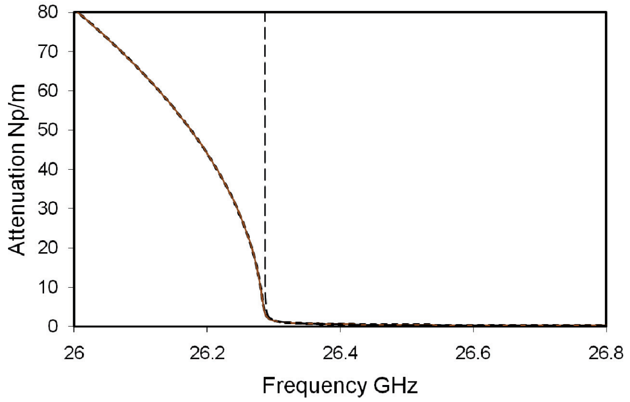

Fig. 5. Loss of TE_{11} mode in a hollow rectangular waveguide near cutoff. ——— our method, — — — — the power-loss method, ▪▪▪▪▪▪▪▪ the PPM.

As expected, equation (20) shows that the cross coupling is significant when the difference between the phase constants of the propagating modes that exist in the waveguide is small. Therefore, we expect that the coupling effect between TE_{11} and TM_{11} in a waveguide fabricated from a good conductor to be significant because the phase constants for TE_{11} and TM_{11} are very close as shown in Fig. 4.

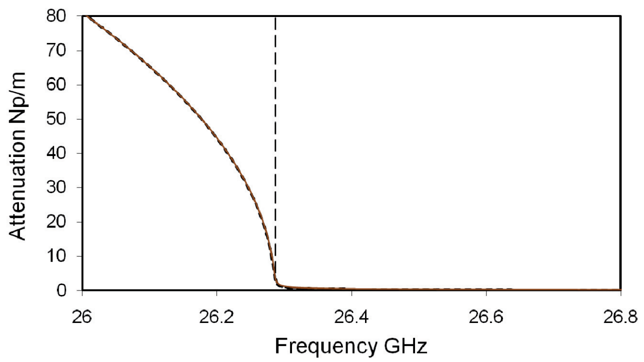

Fig. 6. Loss of TM_{11} mode in a hollow rectangular waveguide from 20 GHz to 100 GHz. ——— our method, — — — — the power-loss method, ▪▪▪▪▪▪▪▪ the PPM.

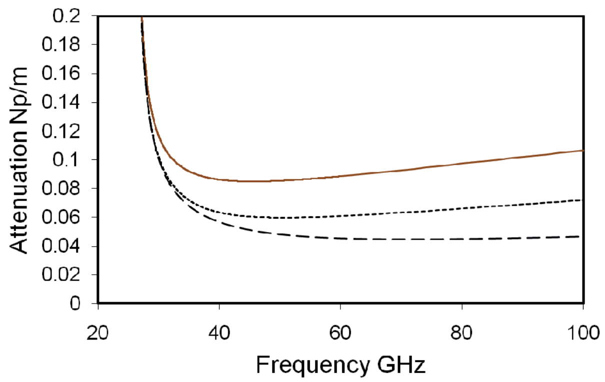

Fig. 7. Loss of TE_{11} mode in a hollow rectangular waveguide from 20 GHz to 100 GHz. ——— our method, — — — — the power-loss method, ▪▪▪▪▪▪▪▪ the PPM.

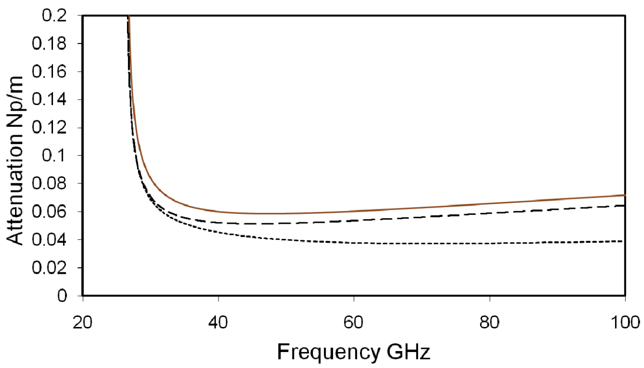

Fig. 8. Loss of TM_{11} mode in a hollow rectangular waveguide from 20 GHz to 100 GHz. ——— our method, — — — — the power-loss method, ▪▪▪▪▪▪▪▪ the PPM.

In Fig. 7 and Fig. 8 we plotted the attenuation constant for the TE_{11} and the TM_{11} modes at frequencies when both of them can propagate simultaneously. It can clearly be seen that in this region, the computed attenuation using our method is significantly higher then the one computed using the power loss method. This is of course to be expected because the power loss method attenuation will exclude coupling losses. It is interesting to see however that in this range, the attenuation computed by PPM is even lower than that obtained by the power loss method, indicating that the PPM method under-estimates the loss significantly in degenerate mode propagation.

4. Conclusion

We have proposed a fundamental and accurate technique to compute the propagation constant of waves in a lossy rectangular waveguide. The formulation is based on matching the electric and magnetic fields at the boundary, and allowing the wavenumbers to take complex values. The resulting electromagnetic fields were used in conjunction with the concept of surface impedance to derive transcendental equations, whose roots give values for the wavenumbers in the x and y directions for different TE or TM modes. The wave propagation constant k_z could then be obtained from k_x, k_y, and k_0 using the dispersion relation.

Our computed attenuation curves are in good agreement with the PPM and experimental results for the case of the dominant TE_{10} mode. An important consequence of this work is the demonstration that the loss computed for degenerate modes propagating simultaneously is not simply additive. In other words, the combined loss of two co-existing modes is higher than adding the losses of two modes propagating independently. This can be explained by the mode coupling effects, which is significant when the phase constants of two propagating modes are different yet very close.

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References

[1] GLASER, J. I. Attenuation and guidance of modes in hollow dielectric waveguides. *IEEE Transactions on Microwave Theory and Techniques (Correspondence)*, 1969, vol. 17, p. 173 – 176.

[2] YASSIN, G., JUNG, G., DIKOVSKY, V., BARBOY, I., KAMBARA, M., CARDWELL, D. A., WITHINGTON, S. Investigation of microwave propagation in high-temperature superconducting waveguides. *IEEE Microwave Guided Wave Letters*, 2001, vol. 11, p. 413 – 415.

[3] YEAP, K. H., THAM, C. Y., YEONG, K. C., WOO, H. J. Wave propagation in lossy and superconducting circular waveguides. *Radioengineering Journal*, 2010, vol. 19, p. 320 – 325.

[4] CLARICOATS, P. J. B. Propagation along unbounded and bounded dielectric rods: Part 1. Propagation along an unbounded dielectric rod. *IEE Monograph*, 1960, 409E, p. 170 – 176.

[5] CLARICOATS, P. J. B. Propagation along unbounded and bounded dielectric rods: Part 2. Propagation along a dielectric rod contained in a circular waveguide. *IEE Monograph*, 1960, 410E, p. 177 – 185.

[6] CHOU, R. C., LEE, S. W. Modal attenuation in multilayered coated waveguides. *IEEE Transactions on Microwave Theory and Techniques*, 1988, vol. 36, p. 1167 – 1176.

[7] STRATTON, J. A. *Electromagnetic Theory*. 1st ed. McGraw-Hill, 1941.

[8] CARTER, M. C., BARYSHEV, A., HARMAN, M., LAZAREFF, B., LAMB, J., NAVARRO, S., JOHN, D., FONTANA, A-L., EDISS, G., THAM, C. Y., WITHINGTON, S., TERCERO, F., NESTI, R., TAN, G-H., SEKIMOTO, Y., MATSUNAGA, M., OGAWA, H., CLAUDE, S. ALMA front-end optics. *Proceedings of the Society of Photo Optical Instrumentation Engineers*, 2004, vol. 5489, p. 1074 – 1084.

[9] BOIFOT, A. M., LIER, E., SCHAUG-PETERSEN, T. Simple and broadband orthomode transducer. *Proceedings of IEE*, 1990, vol. 137, p. 396 – 400.

[10] WITHINGTON, S., CAMPBELL, E., YASSIN, G., THAM, C. Y., WOLFE, S., JACOBS, K. Beam combining superconducting detector for submillimetre-wave astronomical interferometry. *Electronics Letters*, 2003, vol. 39, p. 605 – 606.

[11] SEIDA, O. M. A. Propagation of electromagnetic waves in a rectangular tunnel. *Applied Mathematics and Computation*, 2003, vol. 136, p. 405 – 413.

[12] COLLIN, R. E. *Field Theory of Guided Waves*. 2nd ed. New York: IEEE Press, 1960.

[13] CHENG, D. K. *Field and Waves Electromagnetics*. 1st ed. Addison Wesley, 1989.

[14] BLADEL, J. V. Mode coupling through wall losses in a waveguide. *Electronics Letters*, 1971, vol. 7, p. 178 – 180.

[15] ROBSON, P. N. A variational integral for the propagation coefficient of a cylindrical waveguide with imperfectly conducting walls. *Proceedings of IEE*, 1963, vol. 110, p. 859 – 864.

[16] KOHLER, M., BAYER, H. Feld und ausbreitungskontante im rechteckhohlrohr bei endlicher leifahigkeit des wandmaterials. *Zeitschrift Fur Angewandte Physik*, 1964, vol. 18, p. 16 – 22 (in German).

[17] SOMLO, P. I. HUNTER, J. D. On the TE_{10} mode cutoff frequency in lossy-walled rectangular waveguides. *IEEE Transactions on Instrumentation and Measurement*, 1996, vol. 45, p. 301 – 304.

[18] PAPADOPOULOS, V. M. Propagation of electromagnetic waves in cylindrical waveguides with imperfectly conducting walls. *Quarterly Journal of Mechanics and Applied Mathematics*, 1954, vol. 7, p. 325 – 334.

[19] GUSTINCIC, J. J. A general power loss method for attenuation of cavities and waveguides. *IEEE Transactions on Microwave Theory and Techniques*, 1963, vol. 62, p. 83 – 87.

[20] YEAP, K. H., THAM, C. Y., YASSIN, G., YEONG, K. C. Propagation in lossy rectangular waveguides. In *Electromagnetic Waves* / Book 2. 1st ed. Intech, (to be published in June 2011).

[21] YEAP, K. H., THAM, C. Y., YEONG, K. C., YEAP, K. H. A simple method for calculating attenuation in waveguides. *Frequenz Journal of RF-Engineering and Telecommunications*, 2009, vol. 63, p. 1 – 5.

[22] *The NAG Fortran Library Manual*, Mark 19, The Numerical Algorithm Group Ltd., Oxford, October, 1999.

[23] IMBRIALE, W. A., OTOSHI, T. Y., YEH, C. Power loss for multimode waveguides and its application to beam waveguide systems. *IEEE Transactions on Theory and Techniques*, 1998, vol. 46, p. 523 – 529.

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