Application of Perturbation Theory to Toroidal Ferrite Phase Shifters

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***Abstract*—A new application of perturbation formalism is developed to solve for the phase shift of inhomogeneously loaded waveguides containing ferrite toroids with dielectric inserts. The nonreciprocal differential phase shift is derived explicitly for single and double toroidal phase shifters and agrees with experiment over a broad band of frequencies. The formalism that can take into account the coupling of higher order modes to the fundamental mode by the geometrical inhomogeneities and tensor properties of the ferrite is described. The theory can also be used to evaluate the impedances over a broad bandwidth.**

Introduction

THE ORIGINAL invention of the single slab ferrite phase shifter by Sakiotis and Chait [1] was subsequently replaced by the double slab phase shifter [2]. The theory for both was fully developed by Lax, Button, and Roth [2]. This was modified by Schloeman [3] and by Ince and Stern [4] to include a dielectric slab between two ferrite slabs. This idealized theory has been used for three decades to approximate the more practical toroidal phase shifter developed by Treuhaft and Silber [5] using empirical correction factors derived from experiments. The closed form solution for the single and double toroidal phase shifters is inappropriate for quantitative analysis. Consequently we have developed a perturbation procedure which treats the inhomogeneous geometries more accurately. The theory provides more flexibility and yields explicit expressions for the phase shift involving the dimensions and properties of the ferrite, and the dielectric. It takes into account the demagnetizing and depolarizing factors, as well as the dimensions of the waveguide. In addition the perturbation treatment explores and elucidates the physics of nonreciprocal differential phase shift, the coupling of higher order modes and permits the analysis and correction to the waveguide impedances over a broad band of frequencies.

Perturbation Procedure

The perturbation treatment starts with the expression derived in Lax and Button "Microwave Ferrites and Ferrimagnetics" [6]:

$$\beta - \beta_0 = \frac{\omega \int_{\Delta S} \left[\epsilon_0 \left(\chi_e \cdot \vec{E} \right) \cdot \vec{E}_0^* + \mu_0 \left(\chi_m \cdot \vec{h} \right) \cdot \vec{h}_0^* \right] dS}{\int_S i_z \cdot \left(\vec{E} \times \vec{h}_0^* + \vec{E}_0^* \times \vec{h} \right) dS} \quad (1)$$

where β and β_0 are the perturbed and unperturbed phase shift, χ_e and χ_m are the dielectric and magnetic susceptibilities of the material inserted in the waveguide, ΔS and S are the areas of the inserted materials and the whole guide respectively. The above in (1) is exact if the perturbed field $\vec{E}$ and $\vec{h}$ are correctly represented; normally they are approximated by $\vec{E}_0$ and $\vec{h}_0$, the unperturbed quantities. However in this case for inhomogeneous geometries such as a toroid, we replace the bulk susceptibilities by effective quantities which include depolarizing and demagnetizing factors involving the dimension and shape of the dielectric and ferrite components.

To illustrate the procedure we shall start with the twin-slab ferrite separated by a dielectric slab as shown in Fig. 1. This configuration has an exact solution which results in a transcendental equation using the procedure developed in [2]:

$$\frac{j\beta k_\sigma}{\theta} + k_\sigma k_m \cot k_m \delta - \rho \left(\frac{\beta^2}{\theta^2} - k_m^2 \right) \cot k_\sigma \sigma + \coth k_a a \left(\frac{k_a k_\sigma}{\rho} + j \frac{\beta k_a}{\theta} \cot k_\sigma \sigma - k_a k_m \cot k_\sigma \sigma \cot k_m \delta \right) = 0. \quad (2)$$

This equation is quite involved and contains a number of parameters such as the transverse wave numbers k_a, k_m and k_σ related to the air, ferrite, and dielectric regions respectively, given by the dispersion relations:

$$k_m^2 + \beta^2 = \frac{\omega^2 \epsilon_m \mu_0}{\rho}$$
$$\beta^2 - k_a^2 = \omega^2 \epsilon_0 \mu_0 = \frac{\omega^2}{c^2}$$
$$k_\sigma^2 + \beta^2 = \omega^2 \epsilon \mu_0. \quad (3)$$

Here, ϵ_m, ϵ and ϵ_0 are the permitivities of the ferrite, dielectric and free space, respectively. The terms θ and ρ

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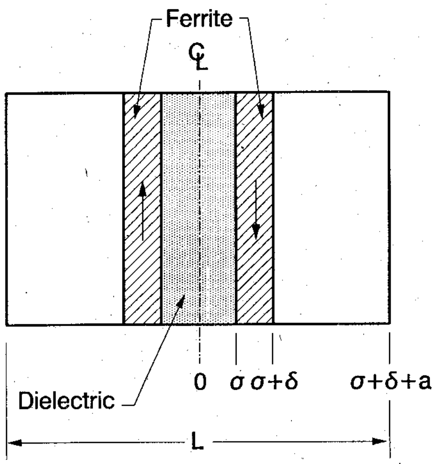

Fig. 1. Twin slab nonreciprocal phase shifter with dielectric arrow indicates direction of magnetization.

are defined by

$$\theta = \frac{1+\chi_{xx}}{\chi_{xy}}; \quad \rho = \frac{1+\chi_{xx}}{(1+\chi_{xx})^2 + (\chi_{xy})^2} \tag{4}$$

where χ_{xx} and χ_{xy} are diagonal and off diagonal susceptibilities of the ferrite as defined in [5].

In order to solve for β the propagation constant, it is necessary to satisfy the full set of (2) and (3). Computer codes have been developed to do this and Ince and Stern [6] have used them to study some of the properties of this configuration by varying the ferrite and dielectric parameters.

The perturbation method is a much simpler technique to apply. First we start by assuming that the ferrite is unmagnetized and treat it as a dielectric. This then uses only the first term in the numerator of (1). We then assume that the dielectric and the ferrite slab represent a monolithic single dielectric with an average dielectric constant. This can be evaluated by setting $\beta - \beta_0 = 0$ and $E = E_o$ using the solution for the TE_{10} dielectric mode (or LSE_{10}) as indicated by Tsandoulas, Temme, and Willworth [7]. When this is evaluated we find

$$\epsilon^{\text{eff}} = \epsilon_m + \Delta\epsilon\left(\frac{2k_{\sigma 0}\sigma + \sin 2k_{\sigma o}\sigma}{2k_{\sigma o}(\sigma+\delta) + \sin 2k_{\sigma o}\sigma}\right) \tag{5}$$

where $\Delta\epsilon = \epsilon - \epsilon_m$.

Now we have a simple dielectrically loaded rectangular waveguide which we can treat in terms of a set of orthonormal LSE and LSM modes. For the lowest TE mode, the TE_{10}, we now turn on the magnetic field and consider the perturbation in terms of the tensor susceptibilities. First we solve two simple simultaneous equations:

$$k_{\sigma 0}\tan k_{\sigma 0}(\sigma+\delta) = k_{a0}\coth k_{a0}a$$

$$k_{a0}^2 + k_{\sigma 0}^2 = \frac{\omega^2}{c^2}(\epsilon^{eff} - 1) \tag{6}$$

for $k_{a0}, k_{\sigma 0}$ using ϵ^{eff} with $k_{ao}, k_{\sigma o}$ representing the unperturbed transverse wave numbers. To evaluate (5) and (6) an iterative procedure is employed. This is a standard problem which is easily solved graphically or on a computer. From this we obtain $\beta_0^2 = \omega^2/c^2 + k_{a0}^2$. This is the value which we use when we evaluate the magnetic perturbation. We are primarily interested in the differential phase shift between the two directions of propagation or the equivalent reversal of the magnetization. We obtain

$$\Delta\beta = 2\chi_{xy}\left(\frac{\cos 2K_{\sigma 0}\sigma - \cos 2k_{\sigma 0}(\sigma+\delta)}{(\sigma+\delta) + \frac{\sin 2k_{\sigma 0}(\sigma+\delta)}{2k_{\sigma 0}} + \left(\frac{k_{\sigma 0}\sin 2k_{\sigma 0}(\sigma+\delta)}{k_{a0}\sinh 2k_{a0}a}\right)\left(\frac{\sinh 2k_{a0}a}{2k_{a0}} - a\right)}\right). \tag{7}$$

This is an explicit expression which is more easily solved in terms of the pertinent parameters as a function of frequency than the transcendental equation of the exact solution. When the two solutions are compared over a broad bandwidth as shown in Fig. 2 the perturbation solution is very close to the closed form results.

Toroidal Phase Shifters

The procedure for the toroidal phase shifter is very similar to that described for the idealized 3-slab geometry. The principal difference is that the configuration is highly inhomogeneous and hence the dielectric and magnetic components each have to be treated in terms of effective susceptibilities which take into account the shape and dimensions. The single toroid shown in Fig. 3. has a rectangular insert inside the toroidal tube. We still consider the composite as a single effective unmagnetized dielectric but this time we make a correction for the electric field inside the dielectric in terms of the depolarizing factors due to the dipole charges at the interface with the ferrite. For the TE_{10} mode this then simplifies the expression in (5) to yield

$$\epsilon^{\text{eff}} = \epsilon_m + \frac{\Delta\epsilon}{1 + N\frac{\Delta\epsilon}{\epsilon_m}}\,\frac{h-2\delta}{h}\,\frac{2k_{\sigma 0}\sigma + \sin 2k_0\sigma}{2k_0(\sigma+\delta) + \sin 2k_0\sigma} \tag{8}$$

where N is the depolarizing factor which depends on the relative dimensions of the rectangular cross section. The other new factor is obtained from the waveguide height $\boldsymbol{h}$ and the thickness of the ferrite tube δ. From this point we then proceed as before solving the two relations shown in (6) for $k_{\sigma 0}$ and k_{a0} again using an iterative procedure. Next we treat the ferrite as a window picture frame in which there are vertical and horizontal sections which are magnetized in opposite directions. For the TE_{10} mode,

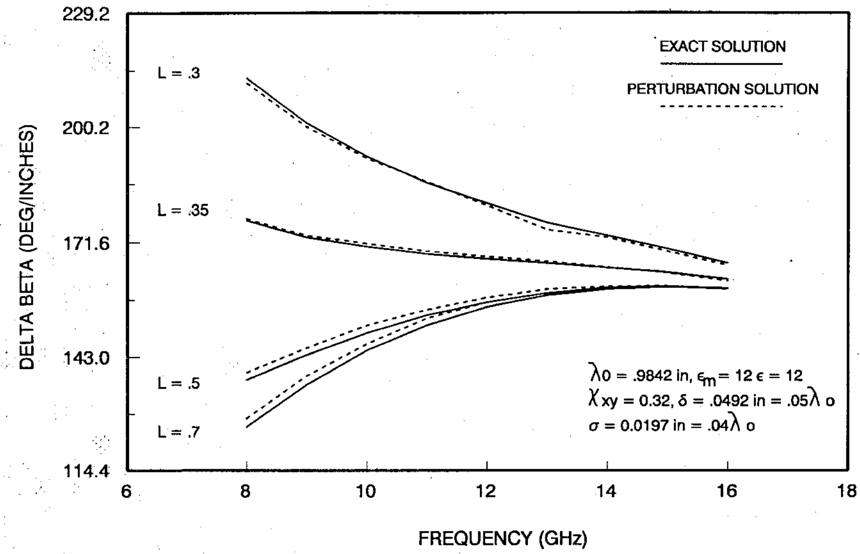

Fig. 2. Comparison of exact and perturbation solution for twin ferrite slab phase shifter with dielectric slab.

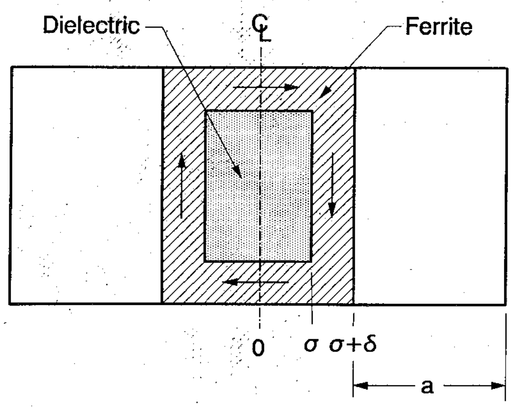

Fig. 3. Toroidal ferrite tube with dielectric insert in rectangular waveguide. Magnetization indicated by arrows.

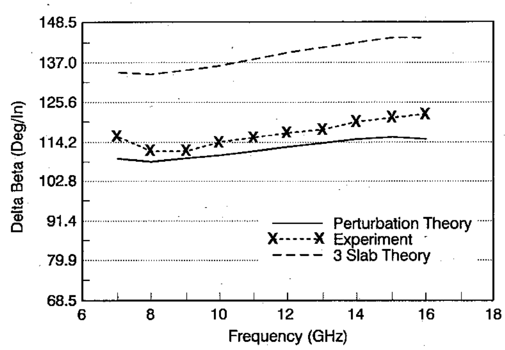

Fig. 4. Comparison of theory and experiment for single toroidal phase shifter. The upper curve is exact solution for idealized twin slab plus dielectric. Lower curve is perturbation treatment of toroid and middle curve is experiment.

the top and bottom of the picture frame, which are magnetized horizontally can be shown not to contribute to the differential phase shift since they cancel one another. Hence only the vertical portions are evaluated. This yields the following expression for the differential phase shift:

$$\Delta\beta = 2\chi_{xy}^{\text{eff}}\frac{h-2\delta}{h}\left[\frac{\cos 2k_{\sigma 0}\sigma - \cos 2k_{\sigma 0}(\sigma+\delta) + \sin 2k_{\sigma 0}(\sigma+\delta)}{(\sigma+\delta) + \dfrac{\sin 2k_{\sigma 0}(\sigma+\delta)}{2k_{\sigma 0}} + \dfrac{k_{\sigma 0}\sin 2k_{\sigma 0}(\sigma+\delta)}{k_{a0}\sinh 2k_{a0}a}\left(\dfrac{\sinh 2k_{a0}a}{2k_{a0}} - a\right)}\right]. \tag{9}$$

Where $\chi_{xy}^{\text{eff}} \approx \omega_m/\omega$ for a saturated ferrite with a zero internal field.

This expression has been used to evaluate the differential phase shift for a single toroid and is compared with experiment and the results of the exact theory using (2) for an equivalent idealized double ferrite slab. This is shown in Fig. 4, which illustrates the superiority of the perturbation treatment which agrees much more closely with experiment.

The double toroid shown in Fig. 5 is separated by a dielectric slab and has two toroidal tubes with rectangular hollow cores. For the sake of generality we shall assume it contains a dielectric. In this instance we first evaluate the effective dielectric constant of the ferrite toroids. This yields an effective dielectric value:

$$\epsilon^{\text{eff}} = \epsilon_m + \frac{\Delta\epsilon}{1+N\dfrac{\Delta\epsilon}{\epsilon_m}}\frac{h-2\delta}{h} \cdot \frac{\left[a-2\delta+\dfrac{\sin 2k_m\delta + \sin 2k_m(a-\delta)}{2k_m}\right]}{\dfrac{a}{2}-\dfrac{\sin 2k_m a}{k_m}}. \tag{10}$$

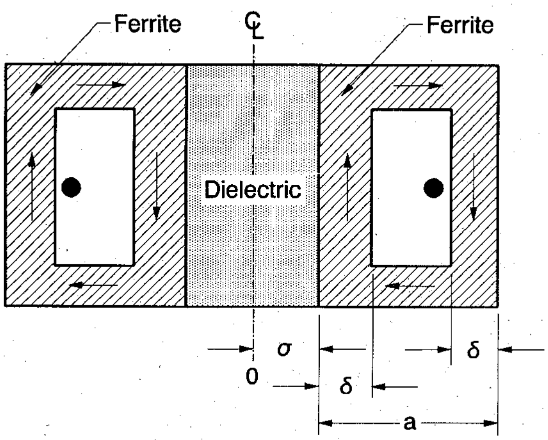

Fig. 5. Double toroidal ferrite phase shifter. Magnetization indicated by arrows.

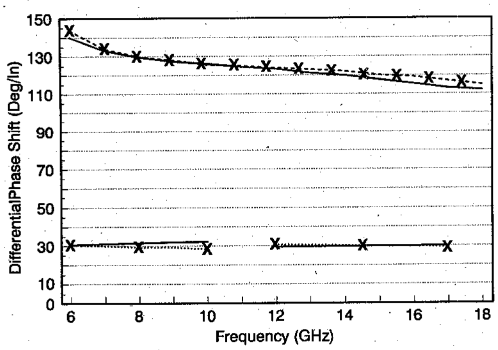

Fig. 6. Broadband toroidal phase shifters. Upper curve is a single toroid, and lower curves are two double toroids, one for low band, the other for high band. Solid curves are theory; the crosses are experimental.

From here on we merely repeat the procedure by solving for the propagation constant, β, using the simple transcendental equation for a dielectrically loaded waveguide represented by (6) solving for and using the relation

$$k_{\sigma 0}^2 + k_{m0}^2 = \frac{\omega^2}{c^2}(\epsilon - \epsilon^{\text{eff}}) \tag{11}$$

where k_{m0} replaces k_{a0} in this case. For the case of a hole in the ferrite tube $\Delta\epsilon = 1 - \epsilon_m$ is negative and hence $\epsilon^{\text{eff}} \ll \epsilon$. Knowing β we are now in a position to turn on the magnetic field and evaluate the differential phase shift for this configuration. The result is evaluated for a displaced window frame geometry which yields similar but somewhat more complicated results. For the sake of brevity we shall not reproduce the expression, which will appear in a future publication dedicated to the quantitative study of double toroidal devices.

The differential phase shift as obtained theoretically is compared with experiment for two such phase shifters and is shown in Fig. 6. The agreement is within a few percent and shows the flat frequency response characteristics of the double toroid phase shifter. The figure also shows another single toroidal phase shifter over a broad band and again the perturbation result is in excellent agreement with experiment.

Higher Order Modes

The perturbation treatment can be carried to higher order to account for the excitation of higher order modes when the phase shifter is operated over a broad band of frequencies. The experiments exhibit the presence of these modes as resonances in the presence of the dominant TE_{10} or LSE_{10} mode. The higher order modes can be coupled to the fundamental mode by the ferrite tensor properties or dielectric inhomogeneities. This can be demonstrated quite readily as follows. Let us assume that the total field in the waveguide is a linear combination of the LSE_{10}, LSE_{11}, LSM_{11} modes labeled with subscripts A, B, and C, respectively, where A, B, C are the coefficients of the linear expansion:

$$\vec{E}_{\text{total}} = A\vec{E}_A + B\vec{E}_B + C\vec{E}_C$$
$$h_{\text{total}} = A\vec{h}_A + B\vec{h}_B + C\vec{h}_C. \tag{12}$$

Equation (13) is obtained by substituting E_{TOTAL} and h_{TOTAL} in (1) and replacing β_o, $\vec{E}_o$ and $\vec{h}_o$ by β_A, $\vec{E}_A$ and $\vec{h}_A$, β_B, $\vec{E}_B$, and $\vec{h}_B$, β_C, $\vec{E}_C$ and $\vec{h}_C$ successively, and $\vec{E} = E_{\text{TOTAL}}$, $\vec{h} = h_{\text{TOTAL}}$. With orthonormal modes we obtain the three linear equations since the denominator of (1) can be set equal to unity but is multiplied by the coefficients A, B, and C.

$$A(\beta - \beta_A) = AM_{AA} + BM_{AB} + CM_{AC}$$
$$B(\beta - \beta_B) = AM_{BA} + BM_{BB} + CM_{BC}$$
$$C(\beta - \beta_C) = AM_{CA} + BM_{CB} + CM_{CC}. \tag{13}$$

When we set the determinant of the coefficients A, B, and C equal to zero we obtain the secular equation for β, the determinant then yields a cubic equation in β corresponding to the three values of the propagation constant at a particular frequency. When this value of β is inserted in any two equations above one can obtain the relative values of the amplitudes of the two higher order modes to the dominant mode. Thus for example values of B/A and C/A yields the magnitude of the coupling to mode A which may be the principal mode launched by the waveguide interfaced with the ferrite phase shifter. If $\beta_A' = \beta_A + M_{AA}$, where M_{AA} is the first order perturbation correction for mode A, then the expansion of the secular equation can be expressed to second order when higher order products of the matrix elements are neglected to yield an expression

$$\beta = \beta_A' + \frac{M_{AB}^2}{\beta_A' - \beta_B'} + \frac{M_{AC}^2}{\beta_A' - \beta_B'}. \tag{14}$$

This result can be generalized to an expansion which includes all higher order modes then the above equation then becomes

$$\beta_i = \beta_i' + \sum_{j \neq i} \frac{M_{ij}^2}{\beta_i' - \beta_j'} \tag{15}$$

where M_{ij} are the coupling matrix elements, expressed for our situation in terms of the diagonal and off diagonal susceptibilities and the orthonormal functions representing all others of the LSM_{mn},LSE_{mn} modes of our dielectrically loaded waveguide characterized by an ϵ^{eff} evaluated for the fundamental modes. Then the matrix elements are the diagonal and off diagonal elements:

$$M_{ii} = \int_{\Delta S} \chi_{\alpha\beta}^{\text{eff}} H_{i\alpha} H_{i\beta}\, dS$$

$$M_{ij} = \int_{\Delta s} \chi_{\alpha\beta}^{\text{eff}} H_{i\alpha} H_{j\beta}\, dS \quad i \neq j$$

$$\alpha, \beta = x, y \tag{16}$$

using the orthonormal relation

$$\int_S \vec{i}_Z \cdot \left(\vec{E}_i \times \vec{h}_j\right) dS = \delta_{ij}. \tag{17}$$

Here $\chi_{\alpha\beta}^{\text{eff}}$ are both the diagonal and off diagonal susceptibilities expressed in terms of demagnetizing factors for each mode as determined by geometrical factors derived and enumerated in [5]. The above procedure gives a good approximation of the coupling of the modes and their contributions to the change in the propagation constant due to the ferrite components.

The information thus obtained can also be used to calculate the impedance and its variation with frequency and magnetic properties of the ferrite. For example expressions for the impedance of the TE and TM modes have been derived in two ways. One is the point or instrinsic impedance at the center of the waveguide which is the ratio of transverse fields of E_y/H_x for the TE mode and TM modes E_x/H_y:

$$Z_{\text{TE}} = \frac{\omega\mu_0}{\beta}, \quad Z_{\text{TM}} = \frac{\beta}{\omega\epsilon} \tag{18}$$

The alternative way is to utilize the relation between the Poynting vector, the current or voltage, the latter in terms of line integrals which yields results effectively equivalent to the above in (18) except for numerical factors and ratios of the rectangular guide dimensions. This leads to the characteristic impedance for the dielectrically loaded guide. The impedance expression for the Poynting vector method is slightly more involved but still proportional to β^{-1} or β for TE and TM, modes respectively:

$$Z_{\text{TE}} = \frac{\omega\mu_0}{\beta} \frac{h}{\dfrac{\cos k_\sigma \sigma}{k_\sigma} + \dfrac{2}{k_a}(1 - \cos k_a a)}$$

$$= \frac{\pi\omega\mu_0}{\beta}\frac{h}{L} \quad \text{(for completely filled guide)}. \tag{19}$$

Where h and L are the dimensions of the waveguide. Similar expressions can be derived for the TM modes. The significant result is that except for numerical and geometrical factors, if one knows beta, the impedance variation with frequency is essentially determined. In the spirit of the perturbation treatment, if the correction due to the magnetic components is relatively small, these can be incorporated into and used in the equations for the impedances. From (19) we then obtain the dispersion of the characteristic impedance.

Conclusion

The perturbation treatment reduces the problem of toroidal ferrite phase shifters to that of an equivalent monolithic dielectrically loaded waveguide. This then forms the basis for the well known LSE_{mn},LSM_{mn} modes represented by an orthonormal set of functions. The deviations from the now established fictitious dielectric waveguide structure consists primarily of the magnetic perturbations, although for higher order modes smaller dielectric perturbations can also be evaluated. In principle then we can calculate the change in the propagation constant using demagnetizing factors to evaluate effective susceptibilities and express the explicit integrals in terms of the unperturbed wave functions for the electromagnetic fields. The results then yield which can incorporate all perturbations, including diagonal and off diagonal components as well as dielectric corrections. In this paper we have illustrated the explicit results only for the nonreciprocal differential phase shift for single and double toroidal phase shifters and found excellent correlation between experiments and theory over a broad band of frequencies.

As a corollary to the extension of the perturbation treatment we have outlined the procedure for including higher order modes. This not only incorporates the perturbation for each mode but also the off-diagonal components in the secular matrix which couples the modes. This can be expanded to second order to include all higher order modes, when cubic and higher products of matrices are neglected. In practice we retain only a few of these terms since only a few of these higher order modes can exist within a practical range of frequencies and the others are cutoff. Hence their contribution can be ignored or neglected as too small within the approximation intended. With the evaluation of the propagation constant for each mode one can also calculate the impedance of the various modes classifying them as TE or TM like which vary as β^{-1} or β with the appropriate geometrical corrections associated with the LSE and LSM modes as indicated by the definition of impedance in terms of the poynting vector and the power relations.

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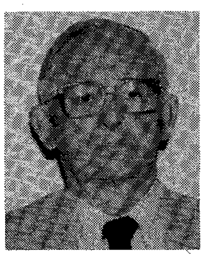

Benjamin Lax was born in Miskolz, Hungary, on December 29, 1915. In 1937 he attended Cooper Union and received the B.M.E. degree in mechanical engineering in 1941. During 1941–1942, he worked for the U.S. Engineers in New York. In 1942 he was inducted into the U.S. Army, attended OCS, then radar school at Harvard and M.I.T. He taught electronics at Harvard until 1944 and was assigned to the M.I.T. Radiation Laboratory as a Radar Officer until 1946. Upon discharge as a Captain, he served as a Radar Consultant to the Sylvania Electric Company prior to entering graduate school at M.I.T. where he received the Ph.D. degree in physics in 1949.

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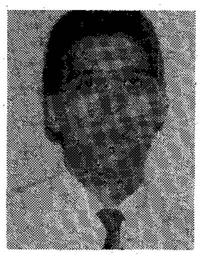

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