Stress-Related Insertion Loss in Longitudinal-Field Ferrite Devices

Charles R. Boyd, Jr.

Microwave Applications Group, Santa Maria, California, 93455, USA

***Abstract* — Some microwave ferrimagnetic materials, e. g. compositions of the yttrium-iron garnet family, are known to exhibit sensitivity to intrinsic or externally applied mechanical stress. This stress can cause the magnetic properties of the material to be inhomogeneous, resulting in undesirable insertion loss increases in devices such as Dual-Mode ferrite phase shifters that use variable longitudinal-field bias. Typically the insertion loss increases appear as "spikes" at low bias field magnitudes.**

This paper presents analyses based on a transmission-line model for the ideal and stress-distorted cases. A conclusion is that the existence of stress-induced inhomogeneities can break the degeneracy of normal modes in the zero-bias condition, causing the observed behavior. A method is suggested for screening ferrite rod samples to determine suitability for use in Dual-Mode phase shifters.

***Index Terms* — Coupled mode analysis, ferrimagnetic materials, ferrites, mechanical factors, phase shifters, stress.**

I. INTRODUCTION

Many years ago during initial development of Dual-Mode ferrite phase shifters [1]-[3], it was thought that it would be desirable to make the phase shifters using rods of gadolinium-doped yttrium-iron garnet material. The objective was to get better temperature stability of phase shift characteristics and a higher operating peak power level than would be possible using spinel ferrites. So a few phase shifters were built with that type of material and put into housings, and the performance data were measured. It came as a surprise to find that the phase shifters performed well except for bias fields near zero flux density, where large "spikes" in the insertion loss were observed. Realizing that garnet material is more sensitive to mechanical stress than spinel ferrite, it was concluded that there was probably some sort of bending stress induced "built-in" transverse magnetic bias field, resulting from the sintering or machining process, or from mounting in the housing, that seemed to be influential only near zero bias field and that was suppressed at higher bias fields. Two lessons were learned from that experience, (i) avoid the use of garnet materials in Dual-Mode ferrite phase shifters, and (ii) try to provide a mounting arrangement that does not subject the ferrite rod to excessive mechanical stresses.

Although the stress sensitivity of garnet materials has been reduced through the addition of dopants such as manganese, it remains possible to have troublesome stresses in a long ferrite rod and consequently those observations made years ago may still affect the performance of Dual-Mode ferrite phase shifters. What has changed with experience is a better understanding of the way stress can influence the behavior of structures with longitudinal bias field, and especially the insertion loss increases near zero bias field levels. The analysis and discussions below seek to examine factors that can lead to the observed behavior, and to suggest a simple screening procedure that can identify ferrite rods that may be unsuitable for use in Dual-Mode ferrite phase shifters. For simplicity and without loss of generality, the analytical model used here is based on waveguides of square cross-section, although the conclusions may properly be extended to waveguides of circular cross-section.

II. SQUARE WAVEGUIDE TRANSMISSION-LINE ANALYSIS

Consider the familiar transmission-line representation for the dominant TE_{10} mode in a uniform, homogeneously filled ordinary rectangular waveguide, shown in Fig. 1. When the distributed series inductance and parallel shunt LC elements are defined as shown, the complex propagation factor γ readily computes to

$$\gamma = \pm\sqrt{ZY} = \pm j\beta_0\sqrt{1-(\omega_c/\omega)^2} \tag{1}$$

where $\beta_0 = \omega\sqrt{\mu\varepsilon}$ is the free space propagation factor in the medium filling the waveguide, and $\omega_c = \pi/a\sqrt{\mu\varepsilon}$ is the cutoff

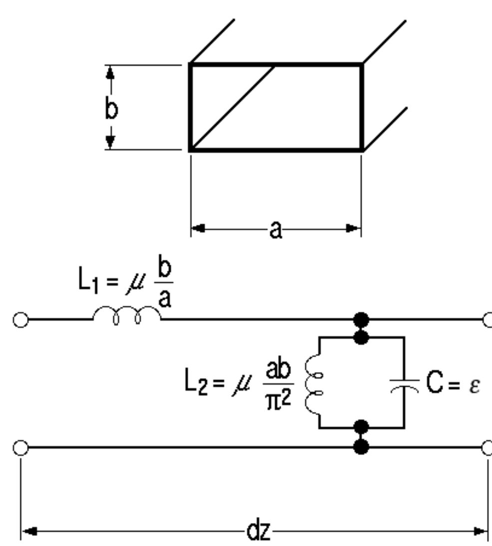

Fig.1. Transmission-line Equivalent Model for Rectangular Waveguide, TE_{10} Mode

frequency of the mode. If the medium is a longitudinally magnetized ferrite in a waveguide constrained so that all modes above the dominant are well below cutoff, then the value for the series-element μ may be taken as μ_{eff}, given by

$$\mu = \mu_{eff} = \mu_d \,[1 - (\kappa / \mu_d)^2]. \tag{2}$$

The shunt-element μ may be taken as μ_z, where expressions for μ_z, μ_d, and κ are well known.

However, if the a and b dimensions of the waveguide are both large enough to support first-order propagating modes, then there will be two sets of transmission-line distributed parameters, which may be taken as L_{101}, L_{110}, L_{201}, L_{210}, C_{01}, and C_{10}. Here the last two digits of the subscript indicate whether the element is associated with the TE_{10} mode or the TE_{01} mode. In the model of Fig. 1, the series inductance elements represent the contribution of the transverse microwave magnetic field, and if it is desired to include the effects of the longitudinal magnetization of the ferrite, some nonreciprocal coupling between the two series inductances must be added. This can be done by writing the two-transmission-line system as a matrix equation, first expressing the series terms by the following:

$$\mathbf{Z} = \frac{j\omega\mu_{eff}}{1-\zeta^2}\begin{bmatrix} \frac{b}{a} & -j\zeta \\ j\zeta & \frac{a}{b} \end{bmatrix}; \tag{3}$$

and the shunt elements by:

$$\mathbf{Y} = j\omega\varepsilon\begin{bmatrix} \frac{a}{b}\left[1-\left(\frac{\omega_{c10}}{\omega}\right)^2\right] & 0 \\ 0 & \frac{b}{a}\left[1-\left(\frac{\omega_{c01}}{\omega}\right)^2\right] \end{bmatrix}. \tag{4}$$

In this notation $\omega_{c10} = \pi / a\sqrt{\mu_z \varepsilon}$ is the cutoff frequency of the TE_{10} mode, $\omega_{c01} = \pi / b\sqrt{\mu_z \varepsilon}$ is the cutoff frequency of the TE_{01} mode, and the parameter ζ represents the level of nonreciprocal coupling that is contributed by a distributed gyrator connected in parallel with the series inductances [4]. This coupling level is related to the ferrite permeability tensor values by

$$\zeta = p\kappa / \mu_d \tag{5}$$

where $0 \le p \le 1$ is a quantity that represents the extent to which the gyrator coupling approaches the coupling of an ideal Faraday rotator. Next, define

$$\beta_{10}^2 = \omega^2 \mu_{eff}\varepsilon\left[1-\left(\frac{\omega_{c10}}{\omega}\right)^2\right] \tag{6}$$

and

$$\beta_{01}^2 = \omega^2 \mu_{eff}\varepsilon\left[1-\left(\frac{\omega_{c01}}{\omega}\right)^2\right] \tag{7}$$

as the uncoupled ($\zeta = 0$) propagation factor terms and form the product of the **Z** and **Y** matrices,

$$\mathbf{K}^2 = \mathbf{ZY} = \frac{1}{1-\zeta^2}\begin{bmatrix} \beta_{10}^2 & -j\zeta\frac{b}{a}\beta_{10}^2 \\ j\zeta\frac{a}{b}\beta_{01}^2 & \beta_{01}^2 \end{bmatrix}. \tag{8}$$

The solutions for the propagation constants β are given by the roots of the characteristic equation,

$$\left[\beta_{10}^2 - \left(1-\zeta^2\right)\beta^2\right]\left[\beta_{01}^2 - \left(1-\zeta^2\right)\beta^2\right] - \zeta^2\beta_{10}^2\beta_{01}^2 = 0 \tag{9}$$

and are

$$\beta = \pm\sqrt{\frac{\beta_{10}^2 + \beta_{01}^2 \pm \sqrt{\left(\beta_{10}^2 - \beta_{01}^2\right)^2 + 4\zeta^2\beta_{10}^2\beta_{01}^2}}{2\left(1-\zeta^2\right)}}. \tag{10}$$

When the nonreciprocal coupling vanishes, i. e. $\zeta = 0$, it is clear that the roots for β are equal to β_{10} and β_{01}. Finally, for the case of a perfectly square waveguide, a and b are equal and consequently $\beta_{10} = \beta_{01} \equiv \beta_0$, so that (10) simplifies immediately to

$$\beta = \frac{\beta_0}{\sqrt{1 \pm \zeta}} \tag{11}$$

The functional relationships of (11) are plotted in Fig. 2 below, with the branches derived from taking the positive or

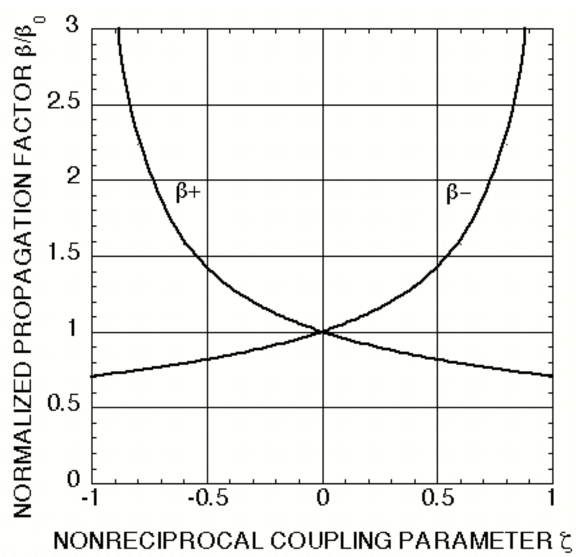

Fig. 2. Propagation Characteristics for Ideal Square Waveguide.

negative sign of ζ so marked. It is important to keep in mind that the normal modes in this ideal square waveguide are right-hand and left-hand circular polarization. Note that when $\zeta = 0$, the two branches cross, implying that for this value only, the two normal modes are degenerate and could be expressed as any orthogonal pair, including linearly polarized, if desired.

III. Stress-Induced Loss of Degeneracy

In a stress-sensitive ferromagnetic material, mechanical stress can distort the magnetic properties of the medium. A long, slender rod of such material can develop a small internal transverse dipole magnetic bias field as a result of bending stress normal to the axis of the rod. A bending stress of this type can be caused by mechanical forces applied externally when the rod is mounted in a misaligned housing. It can also result from mechanical distortion produced by uneven heating of the rod during the sintering process. A rod that is bent during the sintering process may be cleaned up to true mechanical dimensions by subsequent machining, but may nevertheless exhibit a non-homogeneous characteristic with respect to angular orientation of incident linearly polarized microwave excitation. In the absence of a longitudinal magnetic bias field ($\zeta = 0$), there will now be two orthogonal linear normal modes with distinctly different propagation factors. In other words, the normal-mode degeneracy noted for the ideal case of Fig. 2 is gone and the uncoupled propagation factors β_{10} and β_{01} defined above are no longer equal.

The impact on the propagation characteristics is significant, particularly in the vicinity of zero longitudinal magnetic bias field ($\zeta = 0$). To illustrate the effect, take $\beta_{10} = r\beta_0$ and $\beta_{01} = \beta_0/r$, substitute these values into (10) with r set to 1.05 and plot the results shown in Fig. 3.

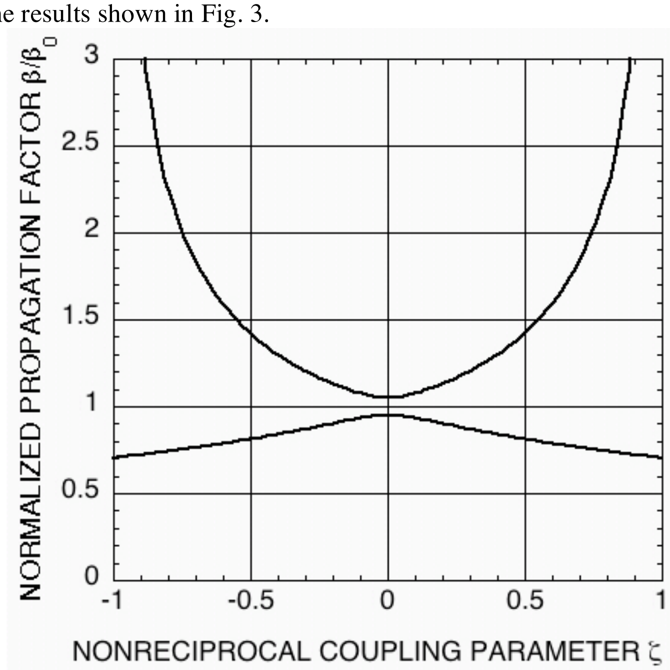

Fig. 3. Propagation Characteristics of Non-ideal Waveguide.

The calculated propagation characteristics of Fig. 3 are somewhat startling at first sight, because there is a range of values of β between β_{10} and β_{01} that cannot be reached regardless of the value selected for ζ. Also, the two branches clearly associated with right-hand (RHCP) and left-hand (LHCP) circular polarization in Fig. 2 are disjoint in Fig. 3, i.e. there is no clear association of one branch with RHCP and the other with LHCP. This is more understandable by recalling that the required normal modes at $\zeta = 0$ are linearly polarized; therefore the normal mode excitation for each branch progresses from one sense of circular polarization, through linear polarization, to the opposite sense of circular polarization as ζ moves from negative values, through zero, to positive values. Fig. 4 shows an expanded plot of the Fig. 3 values for small magnitudes of ζ for the non-ideal case, with the ideal case values overlaid. It is clear that the non-ideal β values, and therefore the normal-mode polarizations, quickly converge to the ideal case values as ζ moves away from zero.

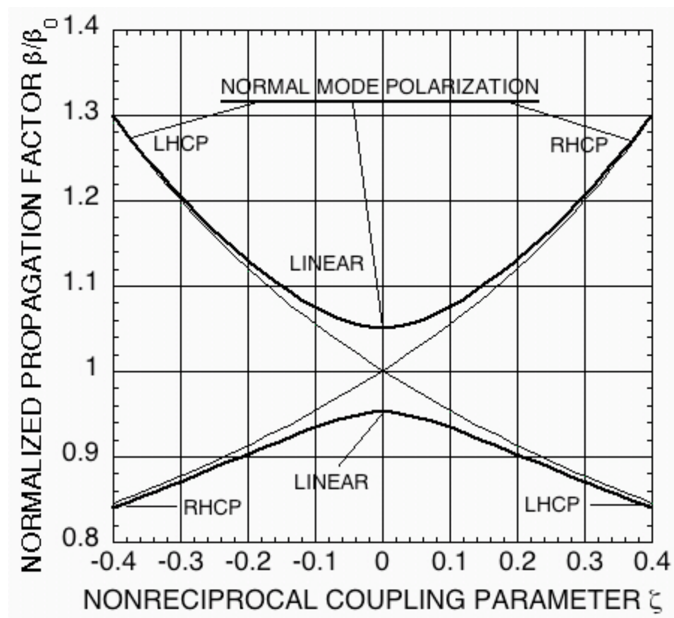

Fig. 4. Comparison of Non-ideal and Ideal Cases.

Splitting of the degeneracy at $\zeta = 0$ can have a profound impact on the performance of a Dual-Mode phase shifter. As the normal-mode phase difference along the rod accumulates, there will be an action to depolarize the incident circular polarization at the input to the variable-field phase shifting section, which will cause an increase of insertion loss though the device. The case r = 1.05 plotted in Fig. 3 is nothing less than catastrophic; because there is about a ten percent difference between the propagation factors β_{10} and β_{01}, there will be a normal-mode phase difference of about 36 degrees per nominal wavelength of the phase shifting section. A typical Dual-Mode phase shifter requires at least three or four wavelengths in the medium to provide 360 degrees of phase shift. Consequently the incident circular polarization will actually be partially converted to opposite-sense circular polarization, with the net effect of increasing the insertion loss of the device by more that 3 dB. For reasonably good device performance, the maximum difference between β_{10} and β_{01} should be no more than about one percent.

IV. "Bimodal Resonance" Screening

Although a constraint of one percent difference between the maximum and minimum β values at zero magnetic bias field seems stringent, there is fortunately a very simple, accurate, and quick method for determining whether a candidate ferrite rod complies with this requirement. The method consists of placing a completely degaussed rod, after metallization, into a fixture which allows the rod to be rotated and which couples its ends lightly to standard waveguide ports. The arrangement is conceptually depicted in Fig. 5.

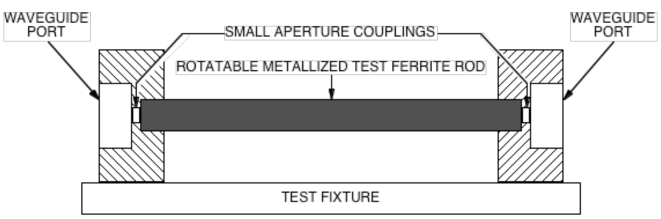

Fig. 5. Rod Screening Test Fixture Concept.

Basically, the rod is operated as a TE_{11n}-mode transmission cavity for a circular cross-section sample, or a TE_{10n}/TE_{01n}-mode cavity for a square cross-section sample. Because the rod length ℓ is many wavelengths long, the frequency band of interest will show periodic resonances of signal coupled to the output waveguide, with the amplitude peaks occurring at successive integer values of the half-wavelength index n. If the rod has principal axes with different propagation constants, there will be a frequency shift back and forth between two sets of periodic resonances as the rod is rotated through 360 degrees. This frequency shift Δf will be exactly the amount needed to cause $\beta\ell = n\pi$ for both normal-mode β values. The magnitude of Δf is related to the difference $\Delta\beta$ between the normal-mode propagation factors by:

$$\frac{\Delta f}{f_0} = \frac{\Delta\beta}{\beta_0}\sqrt{1-\left(\frac{f_c}{f_0}\right)^2} \tag{12}$$

where f_0 and β_0 are nominal values of frequency and propagation factor at a particular resonance, and f_c is the cutoff frequency of the waveguide. The radical generally evaluates to 0.6 -0.7, and if the maximum tolerance for $\Delta\beta/\beta_0$ is 0.01, then the largest acceptable value for $\Delta f/f_0$ will be 0.006-0.007. A criterion of 50 MHz. maximum frequency shift has long been applied by Microwave Applications Group for screening of Dual-Mode ferrite phase shifter rods operating in the 9.0-10.0 GHz. band, a value now seen to be consistent with the one percent limit on variation of β suggested above. Finally, Fig. 6 below shows traces of an X-band bimodal resonance characteristic. In this case the frequency shift appears to be 10 MHz. or less, indicating that the rod is a very good candidate for Dual-Mode ferrite phase shifter use.

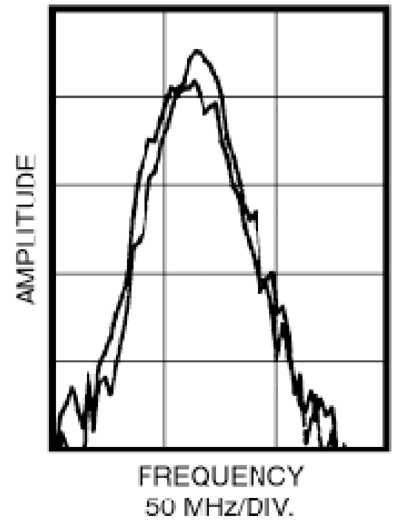

Fig.6 X-band Bimodal Resonance Characteristic Display.

V. Conclusions

A high degree of magnetic symmetry as well as mechanical symmetry is necessary to avoid insertion loss problems in ferrite devices using a long rod operating through longitudinal bias field levels at or near zero. Caution should be used in applying materials known to have stress sensitivity, to avoid "built-in" magnetic distortion. The screening method described above may be helpful in determining suitability for use in such devices. The constraints are less stringent for devices that always operate at substantial bias field levels, such as two-state Faraday Rotation ferrite switching elements.

References

[1] W. E. Hord, C. R. Boyd, Jr., and F. J. Rosenbaum, "Application of Reciprocal Latching Ferrite Phase Shifters to Lightweight Electronic Scanned Phased Arrays," *Proc. IEEE* (Special Issue on Electronic Scanning), Vol. 56, pp. 1931-1939, Nov. 1968.

[2] C. R. Boyd, Jr., "A Dual-Mode Latching Reciprocal Ferrite Phase Shifter," *IEEE Trans. Microwave Theory & Tech.,* vol. 18, no. 12, pp. 1119-1124, Dec. 1970.

[3] C. R. Boyd, Jr., "Comments On The Design and Manufacture of Dual-Mode Reciprocal Latching Ferrite Phase Shifters," *IEEE Trans. Microwave Theory & Tech.,* vol. 22, no. 6, pp. 593-601, June 1974.

[4] C. R. Boyd, Jr., "A Network Model for Transmission Lines with Gyromagnetic Coupling," *IEEE Trans. Microwave Theory & Tech.,* vol. 13, no. 5, pp. 652-662, Sep. 1965.