FINITE ELEMENT MODELING OF FERRITE PHASE SHIFTERS

Steven N. Stitzer
Westinghouse Electric Corp.
Baltimore, MD 21203

Abstract

New full 3-D finite element modeling software has been used to analyze transmission modes in ferrite-based stripline and waveguide devices. Computed results are presented for phase shifters made in twin slab, toroid, microstrip and planar forms. Geometry features such as corner effects and domain magnetization have been analyzed.

Introduction

3-D finite element modeling code named *strat3d*[1,2,3], with the capability of analyzing anisotropic media such as magnetized ferrite, has been developed at Westinghouse. We have used this new code to analyze a variety of ferrite devices, including phase shifters and circulators. The ability to model devices having arbitrary configurations reduces the need for approximate methods based, for example, on transverse resonance, which must neglect such features as corner effects.

The software can analyze 2-dimensional structures such as the cross-section of a transmission line, to give the propagation constant and impedance of each mode. It can also solve a complete 3-dimensional structure such as the matching transition between a phase shifter and straight waveguide. In either case, the problem is partitioned into regions having specified parameters such as dielectric constant, scalar or tensor permeability, conductivity, and loss tangent. A 3-D mesh is created using the I-DEAS™ modeling software from SDRC. The mesh is then linked via custom software to the *strat3d* code where it is analyzed.

Twin-toroid waveguide phase shifter

The twin toroid phase shifter is popular because it produces a high phase shift per dB insertion loss. The differential phase shift attained in this structure is controlled by varying the magnetization in the ferrite. This changes the tensor permeability[4], thereby changing the propagation constant in the waveguide. The toroidal shape of the ferrite is used to form a magnetically latchable structure so that magnetizing current need not be applied continuously. A pulse of current fed through a wire that threads the toroid leaves a remanent magnetization M_r in the ferrite. It is found that if the toroids are magnetized in the same direction, the maximum differential phase shift is obtained by switching the magnetization between $+M_r$ and $-M_r$. If the corresponding propagation constants are k^+ and k^-, the differential phase shift is just $k^+ - k^-$, in units of phase shift per unit length.

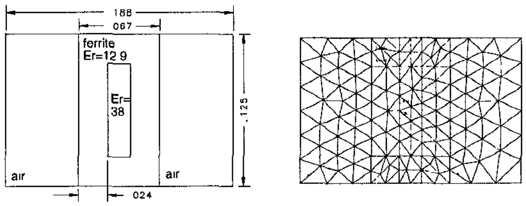

Figure 1. Cross section of single toroid phaser and mesh used for calculations (dimensions in inches).

Figure 1 shows the dimensions of a Ku-band twin toroid phase shifter used for these calculations. The mesh used to evaluate the propagation constant and impedances of the structure is also shown. A value of $4\pi M_r$=2000 gauss was assumed for the ferrite. Figure 2 shows the calculated propagation constants for M = $+M_r$, 0, and $-M_r$. The dominant mode is similar to the rectangular waveguide TE_{10} mode, but is more highly concentrated at the center of the guide. Higher order modes can also propagate in the structure. RF energy coupled into these modes can interfere with the dominant wave, producing ripple in the transmission and increased VSWR. Mode 2 is an LSE type which cuts off around 13-14 GHz, depending on the magnetization. Mode 3 is complex. As with evanescent modes, complex modes store energy rather than dissipate it, and decay in amplitude with distance from their point of origin. Unlike ordinary evanescent modes, complex modes have an oscillatory magnitude. Complex modes take part in the mode matching at interfaces such as between the end of the toroid section and the adjacent matching section to rectangular waveguide. Not all modeling codes seem to be able to find these complex modes in the 2-D port model. This suggests that there may be missing details in a full 3-D analysis if the ports are moved too close to internal structural discontinuities.

The impedance of the twin toroid phase shifter varies as the magnetization and phase shift are changed. The power-current impedance Z_{pi} is based on the RF current in the top wall of the phase shifter. The power-voltage impedance is based on the voltage $\int E_y dy$ across the centerline of the rib. Figure 3 is a plot of Z_{pi} and Z_{pv} versus frequency for $M=-M_r$, 0, and $+M_r$.

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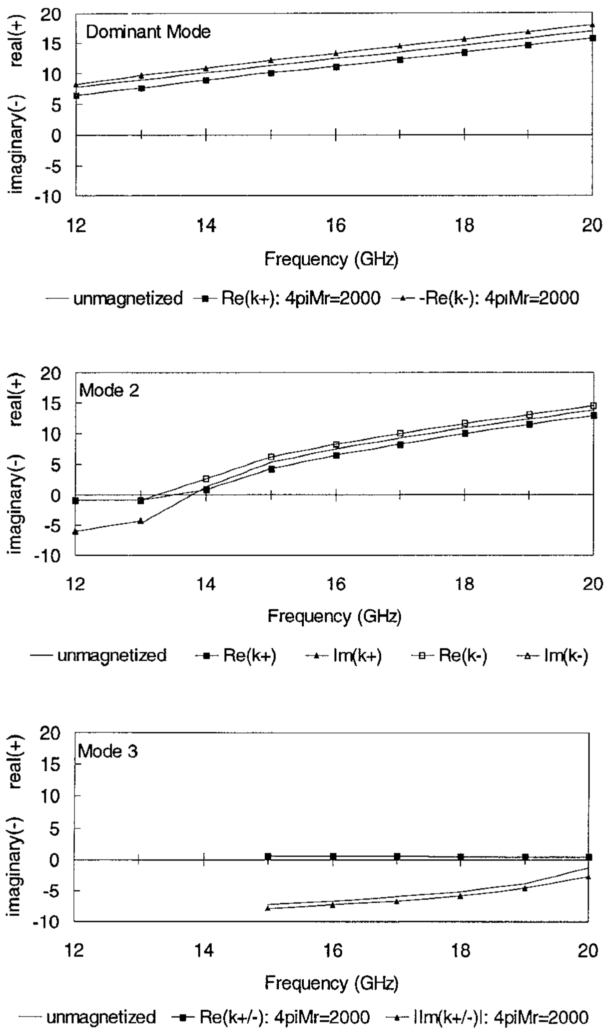


Figure 2. Calculated propagation constant k(/cm) for three modes in Ku-band twin-toroid phase shifter.

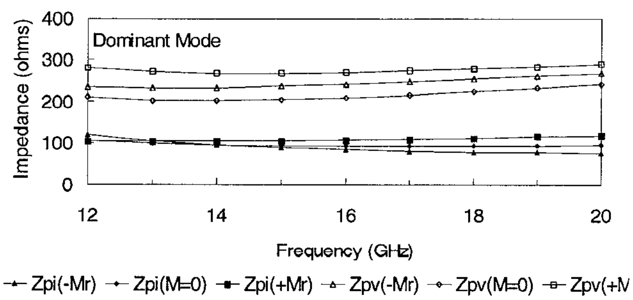


Figure 3. Calculated impedances in twin toroid phase shifter at three magnetizations.

Corner effects

It is useful to compare the calculated results of the idealized twin-slab version to the analytical solution. The twin-slab model assumes that the magnetization is uniform in each leg of the magnetic path. This cannot be true in the corners of the toroid version[5], where the flux must bend around to the top and bottom walls. This gives a less favorable relationship between the RF magnetic field and the DC magnetization in these parts of the ferrite. As a result, the twin toroid provides less phase shift than does the twin slab.

A better approximation is to partition the ferrite legs into regions, each having the same dielectric constant and magnetization, but with the magnetization oriented differently in each region. See figure 4. The outer corners of the toroids can be specified as ferrite having zero magnetization, or as material with a different dielectric constant, if the corners are chamfered. Table I compares the calculated phase shift for different versions of the phase shifter, with the same materials and ferrite wall thickness.

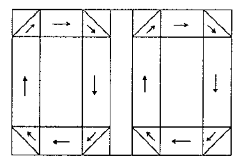


Figure 4. Magnetization scheme in twin toroid phase shifter with unmagnetized corners.

TABLE I Calculated Differential Phase Shift for Various Phase Shifters

Type	Corners	k+ (/cm)	k- (/cm)	Diff Phase Shift(°/cm)
Twin Slab	none	10.469	13.528	175.3
Twin Toroid	square*	11.178	13.263	119.5
"	45°,unmag	11.165	13.261	120.1
"	45°,air	11.171	13.263	120.0
Single Toroid	square*	11.108	8.916	125.6
"	45°,unmag	11.062	9.026	116.7
"	45°,air	9.570	7.374	125.8

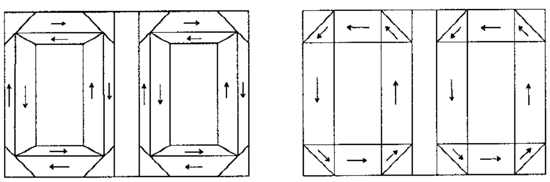
* - unrealistic magnetization

The single toroid is another version of the phase shifter. Different results are to be expected for single and twin toroids because the dielectric rib does not extend the full height of the waveguide in the single toroid, and the outermost and top and bottom walls are not present in the single toroid. In the twin toroid, chamfering the outer corners, which are far away from the center, has little effect on phase shift. In the single toroid case, leaving the outer corners unmagnetized reduces the phase shift by several °/cm. Removing the corners restores the phase shift. This trend is in agreement with measured results at S-band[6].

Note that the propagation constant changes sense between single and twin toroids because the magnetization of the innermost walls is reversed between single and twin toroids magnetized in the same direction.

Magnetic Domains

Ferrite phase shifter analysis usually assumes that the ferrite has a uniform value of magnetization M throughout the volume, with $-M_r \leq M \leq +M_r$. This is not the true state of the magnetization. In reality, the ferrite is divided into domains, each of which is always at saturation magnetization M_S [5,7]. Differences in magnetization come about because the size or orientation of the domains can be changed by applying an external field. The net magnetization in the ferrite, as might be measured in a B-H loop test, is the *vector* average of the magnetizations of all the domains. One might argue that the domains are likely to be quite small compared to the RF wavelength in a waveguide phase shifter, and therefore this average is a suitable value to use for the whole ferrite. However, the magnetization of the toroids is accomplished by a current-carrying wire passed through the toroid, and the magnetic field around the wire is not uniform. The inner regions of the toroid, which are closest to the wire, are driven further past H_c than are the outer regions. Figure 5 shows plausible (albeit simplistic) domain configurations for a toroid at different net magnetizations. The RF magnetic field is not uniform in the ferrite, so local differences in the direction of the magnetization will produce different results.



Toroids Partially Set: $-M_r \leq M \leq +M_r$

Toroids Fully Set: $M = +M_r$

Figure 5. Plausible domains in twin toroid phase shifter magnetized by internal wire. Compare with Figure 4.

For computational purposes, we divided each vertical wall in a twin slab phase shifter into four domains as shown in Figure 6. The magnetization in each domain was kept constant at M_S, changing only in direction from state to state. The four layers allowed five net magnetization states to be evaluated.

Table II gives the wavenumber and phase shift for each magnetization state, along with the values assuming a continuously variable uniform magnetization in the entire volume. The fully saturated endpoints give the same phase shift, but there are differences everywhere else. It should be noted also that the deviation from the uniform M case is reversed between single and twin toroids because the region of domain reversal progresses from the waveguide centerline outward when a single toroid is pulsed, but *toward* the centerline when twin toroids are pulsed. The inner wall magnetizations go as:

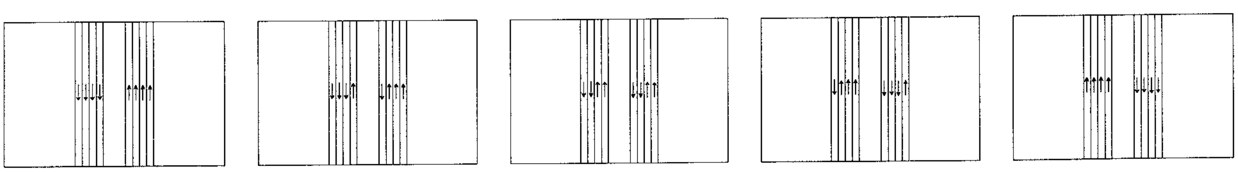
```
single toroid:
---- ++++  ---+ -+++  --++ --++  -+++ ---+  ++++ ----
twin toroid:
---- ++++  +--- +++-  ++-- ++--  +++- +++-  ++++ ----
```

TABLE II Wavenumber in Domain Layered Twin Slab Phase Shifter

Domain Layers:				
----|++++	---+|-+++	--++|--++	-+++|---+	++++|----
k(/cm)				
10.412	11.245	12.104	12.868	13.470
Δφ(°/cm)				
0	47.7	96.9	140.7	175.2
Uniform M:				
$-M_r \mid +M_r$	$-M_r/2 \mid +M_r/2$	0 | 0	$+M_r/2 \mid -M_r/2$	$+M_r \mid -M_r$
k(/cm)				
10.412	11.287	12.092	12.820	13.470
Δφ(°/cm)				
0	50.1	96.3	138.0	175.2

Stripline structures

The code can be used to analyze transmission media such as microstrip, stripline, coplanar waveguide, and slot lines. Microstrip and slotline phase shifter analyses have been published recently[8]. We used the new code to evaluate the propagation constant in one case; good agreement is found as shown in figure 7.



$M_r=+M_s$ $M_r=+M_s/2$ $M_r=0$ $M_r=-M_s/2$ $M_r=-M_s$

Figure 6. Magnetic domains assumed for twin slab phase shifter calculations.

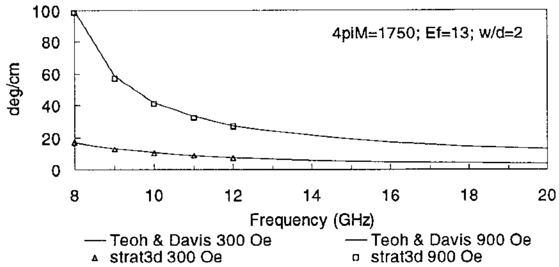


Figure 7. Phase shift in microstrip on ferrite substrate, H applied parallel to microstrip, compared to Teoh and Davis [8].

Circulators

We have modeled stripline and microstrip circulators with the new code. Figure 8 shows the geometry of a high power stripline circulator for 1.3 GHz. An electromagnet with 4" diameter pole pieces was used to apply a field of 2050 Oe. A uniform internal field of 850 Oe was assumed for the calculation. Figure 9 compares the measured and calculated S-parameters. The main differerence is a slight upward frequency shift in the calculated response. This is probably due to uncertainty in the magnetization inside the ferrite.

In microstrip models done to date, circulation is predicted, but the computed return loss and isolation have not been as good as has been measured in actual hardware. This may be due to uncertainty in the exact magnetic state of the ferrite when it is magnetized by small permanent magnets. Also, there may be errors in the model due to inadequate analysis of field singularities at the edges of very thin strip conductors.

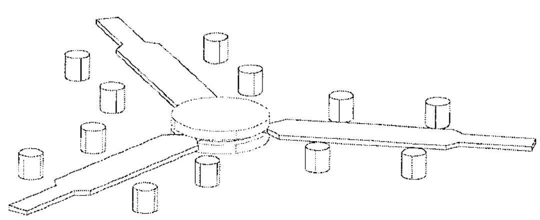


Figure 8. Experimental L-band stripline circulator. The YIG pucks are 1" dia. x 0.1" thick. The resonator disk is 0.84" dia. and the 30.8 Ω matching sections are 79º long. The center conductor is 0.05" thick copper. Total ground plane spacing is 0.25". The 12 cylinders surrounding the circuit are grounding posts.

Conclusions

Finite element code has been used to evaluate the effects of differences in geometry and magnetic domain effects, in magnetized ferrite transmission media. This will be of great value in designing complicated ferrite structures for which no analytical models exist.

Acknowledgments

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References

1. T. P. Fontana, E. W. Lucas, "A Generalized Et-Ht Formulation for the Eigenmode Analysis of Lossy, Anisotropic Uniform Waveguides", IEEE A-P Symposium Digest, June, 1994, pp. 1744-1747.
2. E. W. Lucas, T. P. Fontana, "Vector Finite Element Implementation of the Variational Et-Ht Generalized Eigenmode Formulation", IEEE A-P Symposium Digest, June, 1994, pp. 1764-1767.
3. E. W. Lucas, T. P. Fontana, "A 3-D Hybrid Finite Element/Boundary Element Method for the Unified Radiation and Scattering Analysis of General Infinite Periodic Arrays", IEEE Trans AP-43, February, 1995.
4. B. Lax & K. J. Button, Microwave Ferrites and Ferrimagnetics, Chapter 4, McGraw-Hill, 1962.
5. G. P. Rodrigue, et al, "Operating Dynamics and Performance Limitations of Ferrite Digital Phase Shifters", IEEE Trans MTT-15 December, 1967, pp. 709-713.
6. W. J. Ince, et al, "Toroid Corner Chamfering as a Method of Improving the Figure of Merit of Latching Ferrite Phasers", IEEE Trans MTT-19, June, 1971, pp. 563-564.
7. R. M. Bozorth, Ferromagnetism, D. van Norstrand, 1951.
8. C. S. Teoh, L. E. Davis, "A Comparison of the Phase Shift Characteristics of Axially-Magnetized Microstrip and Slotline on Ferrite", 1995 Intermag Conference, IEEE Trans Mag-31, November, 1995, pp. 3464-3466.

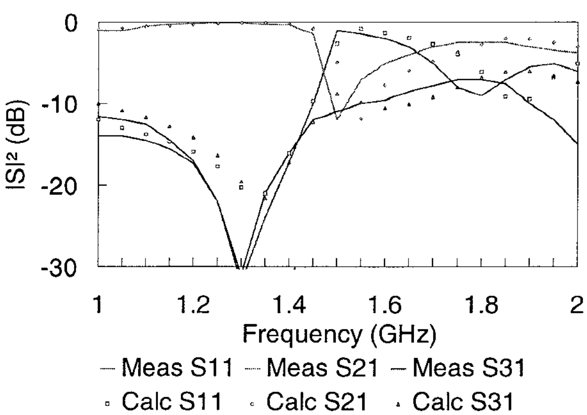

Figure 9. Comparison of measured and calculated S-parameters of the circulator in figure 8.