FERRITE-EIELECTRIC COMPOSITE INTEGRATED MICROWAVE CIRCUIT DEVELOPMENT (INVITED)

C. G. Aumiller
Syracuse University Research Corp.
Syracuse, N.Y.

D. H. Harris and M. C. Willson
Monsanto Research Corp.
Dayton, Ohio

Y. S. Wu and F. J. Rosenbaum
Washington University
St. Louis, Mo.

D. L. LaCombe
Monsanto Microwave Products
St. Louis, Mo.

Introduction

The Arc Plasma Spray process (APS) makes possible the fabrication of complex ferrite/dielectric composite structures suitable for use as substrates for microwave integrated circuits.[1] A typical two layered microstrip geometry is shown in the insert of Fig. 2. The usual microstrip design problems are now complicated because of the choice possible in the selection of the ferrite and dielectric material constants (dielectric constant and permeability) and the relative heights of the two materials. As an example of the structures possible, a substrate for a non-reciprocal latching meanderline phase shifter is shown in Fig. 1. TT1-390 ferrite material was deposited in a preformed cavity of a 0.035" substrate with $\varepsilon_d = 13$. A metallization is made and the meanderline structure is formed. Circulators, filters, etc., can be fabricated in the same fashion. Some of the advantages of this approach are: a) the design of previously unavailable circuits is now feasible, b) ferrite materials can be deposited only where they are required in a given circuit, c) the ferrite microwave properties are maintained or enhanced through the APS process, d) high power handling capability is now possible in planar MIC's and e) potential cost savings.

In order to understand and exploit this new MIC transmission medium, detailed studies of the microwave propagation properties, magnetic field dependence and characteristic impedance of the ferrite/dielectric composite substrates have been investigated. Phase shifter geometries in microstrip, coplanar waveguide (CPW) and slotline have been studied and usable phase shifters with peak power handling capability in excess of 1 KW have been developed.

Theoretical Studies

We have considered an infinite parallel plane waveguide with perfectly conducting top and bottom walls, filled with the composite medium as a first approximation to the propagation characteristics of the lowest order mode (insert, Fig. 2). The ferrite is magnetized in the Z direction with a dc bias field H_o. Wave propagation is in the Y direction. The boundary value problem for the fields can be stated exactly and solved numerically via computer. A frequency-propagation constant (f-β) diagram is shown in Fig. 1 for a given ferrite/dielectric composite with bias field as the parameter. Two branches are shown with a cut-off (high attenuation) region separating them in the region of ferrimagnetic resonance. This (f-β diagram is similar to that obtained for propagation in a transversely magnetized infinite ferrite medium.

In order to validate the use of our approximation to predict the characteristics of microstrip propagation, an edge coupled ring resonator was constructed using a solid ferrite substrate and the resonant frequencies of the ring in the range 4-12 GHz were measured as a function of magnetic bias field. Good agreement (within 4%) between theory and experiment was obtained by using the infinite waveguide analysis, modifying the results with Wheelers' approximation for the effective dielectric constant.[2] Fig. 3 is a comparison of the theoretical attenuation in db/me for the solid substrate and various composite geometries. Note that the high attenuation band is narrower for the composite medium then for the solid substrate. The minimum theoretical attenuation (assuming conductor loss only) is about 0.1 db/in.

The theoretical attenuation for the ferrite/composite medium is less than that for the total ferrite medium because of the difference in the lowest order modes in these structures. In the total ferrite medium, the dominant mode is a TE_0 mode whose longitudinal electric field is not large, leading to quasi-TEM propagation. In the composite medium the difference in the dielectric and magnetic properties of the layers leads to a dominant mode with 6 field components; a hybrid mode. If the relative dielectric constant of the dielectric layer (ε_d) is made less than that of the ferrite (ε_f), then the energy storage per unit volume and the propagation constants will be different than that for the ferrite medium case.

The difference in field configurations leads to a difference in wall currents, and hence the lower loss. Wall currents on the top and bottom conductors in the composite waveguide are not equal. These circumstances can be used to reduce the magnetic field intensity in the ferrite layer and allow a greater power handling capability.

Fig. 4 compares the characteristic impedance of total ferrite and a composite waveguide. The calculation is made on the basis of equal top and bottom strip widths, using the "voltage current" definition, $Z_{V,I}$. The analytical expression for the solid substrate impedance is

$$Z_{V,I} = Z_0 \frac{h}{w} \frac{\mu_{eff}}{\varepsilon_f} \quad (1)$$

where h is the substrate thickness, w is the strip width, Z_0 is the characteristic impedance of free space, ε_f and μ_{eff} are the dielectric constant and effective permeability of the ferrite respectively.

The theoretical frequency and magnetic field dependencies of Eq. (1) are in good agreement with the experimentally measured characteristics and general behavior for composite microstrip is similar to the solid substrate results.

A magnetic filling factor, defined as the ratio of the magnetic energy stored in the ferrite to the total stored energy, has been calculated as shown in Fig. 5. This quantity is a measure of the magnetic interaction that can be achieved in composite structures. It too reflects the dispersive character of the ferrite microstrip and has a cutoff region related to that shown in Fig. 1.

Experimental Devices

The first experiments to demonstrate improved peak power handling capability were performed with meander line type devices. Fig. 6 presents data on dielectric/ferrite composites and meander line circuit configurations. Circuit (4) is a total ferrite substrate, a standard for this experiment that was developed earlier for the Air Force Avionics Laboratory.[3] This device has a nonlinear loss break point of approximately 10 watts and a phase shift of 360°±10° over 10% bandwidth. In circuits (1) and (2) the meander line configurations are identical and only the dielectric space material varies with ε ranging between 7 and 13. It is evident that the lower ε yields more phase shift and a higher nonlinear loss break point. In Circuit (3) the element spacing between meander lines has been changed from 0.0065" to 0.0085". In comparing (1) and (3), it can be observed that the phase shift was doubled and the peak power break point was increased by approximately a factor of five. The latched phase shift increase was due to the fact that the quality of circular polarization was improved in the ferrite because of the gap increase. The factor of less line-to-line coupling also helped to increase the non-linear loss break point. The peak phase shift of Circuit (3) is still about half Circuit (2) even though it has about twice the power handling ability. The loss of the three samples was higher than anticipated because the finish on all three was about 24μ in., which causes a 25% increase in loss above the normal 5μ in. finish which is present on Circuit (4). It can be observed that there is a definite trade-off between peak phase shift and high power capability.

Slotline phase shifters have also been examined using composite substrates and show similar phase shift-high power trade-off possibilities. Representative phase and high power characteristics of an 0.008" slotline on TT1-390/D13 composite (slotline on ferrite) was 40°/in. at 100 watts, but losses were disappointingly high. An 0.016" slotline was placed on a solid TT1-105 (0.025" thick). A similar 40°/in. maximum phase shift was observed with a 100 watt capability. This device was top loaded using a second 0.025" TT1-105 ferrite wafer. Phase shift characteristics increased to 70°/in. with power capabilities >1KW. Figures of merit were a disappointing 17.5 and 36°/dB respectively.

In the investigation of the coplanar waveguide device,[5] the results obtained so far show that this mode of propagation yields the best figure of merit and power handling capability. In Fig. 7 it can be observed that CPW on

TT1-390 and D-7 ($Al_2O_3 \cdot MgO$ + 40% MgO) achieved high phase shift and better power handling than the corresponding CPW circuit on TT1-390 and D13. The total differential phase shift is achieved by exciting the CPW device with first a transverse magnetic field (100 oe) and then with a longitudinal magnetic field (100 oe). From the transverse magnetization component, a 15% nonreciprocal effect is present in the total phase shift.

Circuits (2) and (4) show that TT1-390/D-7 composite yields a peak phase shift of 95° and a nonlinear loss break point of ≈300 watts whereas the TT1-390/D-13 composite only has ≈60° and a break point of 100 watts. Circuits (1) through (3) of Fig. 7 show the effects on phase shift and high power if W (center conductor width) and S (spacing from W to ground) is varied. There is a direct trade-off between the two in that as the nonlinear loss break point increases, the maximum phase shift decreases. The loss of Circuits (1) through (3) decreases as the phase shift decreases, but the figure of merit of the three is very good as is shown. The high loss on Circuit (4) is due to the metallization technique and surface porosity.

The overall results of the experimental investigation slotline, co-planar waveguide and meander line composite devices show promise. Some thought has been given to improving the figure of merit by using the technique of placing ferrite materials at the point of maximum interaction in slotline, CPW and meander line. This technique allows the device to remain planar with mesas of ferrite strategically located. It appears promising ferrimagnetic/dielectric composite devices could very well be developed that yield a high power, low cost phase shifter for large scale integration.

References

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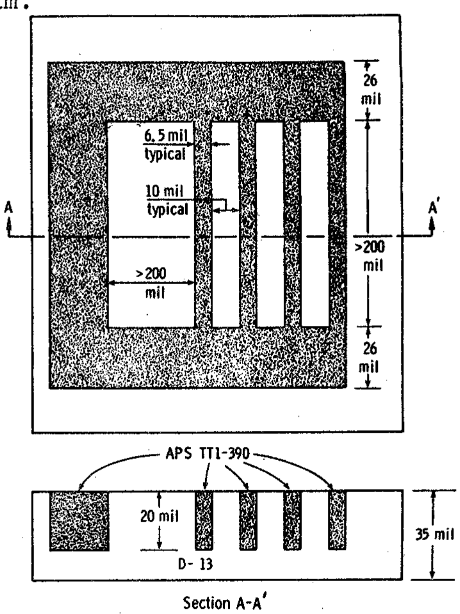

Figure 1. Latching Phase Shifter Substrate.

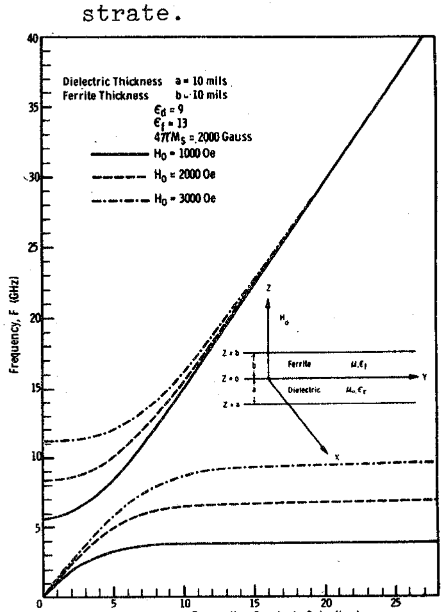

Figure 2. Theoretical Dispersion Diagram of Composite Waveguide.

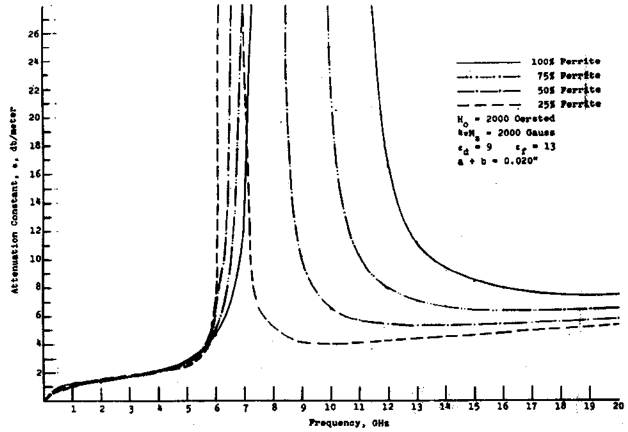

Figure 3. Attenuation Constant of Ferrite/Dielectric Composite.

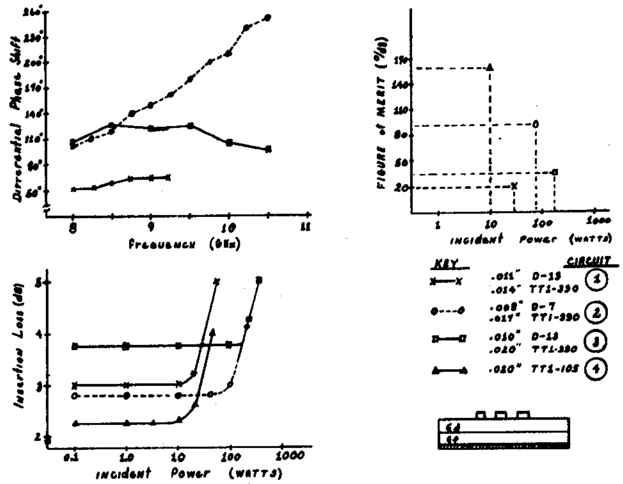

Figure 6. Meander Line Performance.

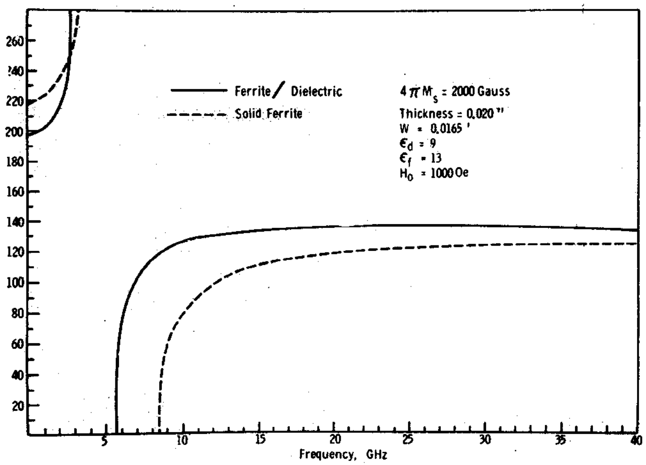

Figure 4. Comparison of Impedance for Solid Substrate and Composite Microstrip.

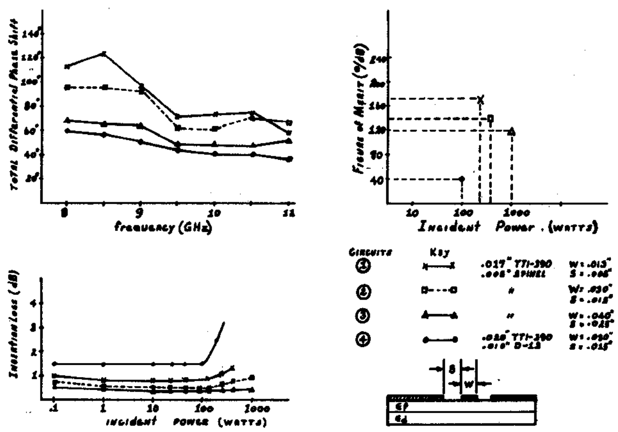

Figure 7. Co-planar Waveguide Performance.

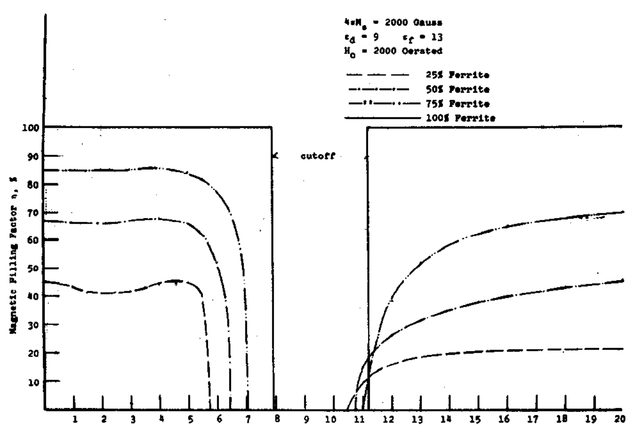

Figure 5. Magnetic Filling Factor of the Composite.