Correspondence

Microstrip Junction Circulator for Microwave Integrated Circuits

This author has reported recently on two forms of microstrip junction circulators.[1],[2] In the first type, a garnet disk was cemented into a ceramic substrate to form a composite ceramic substrate. Copper ground plane, quarterwave microstrip transmission lines, and disk were evaporated onto this substrate following a chrome flash. In the second form, the microstrip junction circulator was fabricated from a single garnet subtrate. The lines, ground plane, and disk were evaporated exactly as in the first case. The results were published as preliminary feasibility test data.[2] This all-garnet substrate circulator was identical in size with the composite ceramic substrate. The results were sufficiently promising to warrant a new smaller design size for the all-garnet microstrip junction circulator because the dielectric constant of the garnet substrate was larger than that of the ceramic.

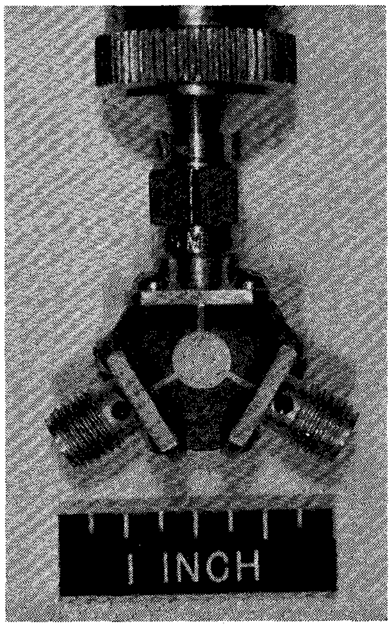

Fig. 1. Photograph of an X-band ferrimagnetic substrate microstrip junction circulator (garnet).

Fig. 1 is a photograph of the revised x-band all-garnet microstrip junction circulator. The substrate is 0.023 inch thick with a copper disk center 0.21 inch in diameter. A small platinum-cobalt magnet, 0.1 inch long and 0.3 inch diameter, is located on the underside of the substrate ground plane. OSM connectors (and transition to type N) are used to permit testing of the device. The insertion loss data presented in this correspondence include the loss in the microstrip to OSM transition. The microstrip transmission lines are approximately a quarter wavelength long at 9.0 GHz, as calculated from design curves presented in a recent report.[3] The cylindrical inner conductor of the OSM connector is taken down to a rectangular cross section of approximately 0.010 inch thickness and 0.010 to 0.025 inch width (depending on the transmission linewidth). The inner conductor of the OSM connector extends 0.010 inch from the connector and makes a press contact with the copper line on the substrate.

Figs. 2 and 3 are graphs of early data obtained with the smaller size all-garnet junction circulator. Fig. 2 represents data taken with an electromagnet. The 20 dB isolation bandwidth is almost 13 percent with an insertion loss less than, or equal to, 0.45 dB over this entire band. The minimum insertion loss of 0.15 dB occurs at the frequency for maximum isolation. In Fig. 3 a broadbanding effect with the small platinum-cobalt magnet is evident. The 20 dB isolation bandwidth is about 20 percent while the insertion loss over this band is less than, or equal to, 0.45 dB with the exception of the lower frequency band edge where it rises to 0.6 dB and then drops. The minimum insertion loss is 0.15 dB and occurs at about the same frequency as with the electromagnet biasing field. However, the peak isolation frequency is shifted downward. The nonuniform dc magnetic biasing field from the platinum-cobalt magnet appears to stagger-tune the junction region, and hence, provides the improved bandwidth. This effect was observed with the early larger all-garnet circulator.[2] Some or all of this tuning effect must take place in the quarterwave transformer section on the magnetic substrate because the broadbanding phenomenon was not evident in the data on the composite ceramic substrate.[1] The increase in insertion loss at the low-frequency end was removed when the inner tab of the OSM connector was carefully machined flat. In fact, under these conditions 20 dB isolation bandwidths of 28 percent were obtained with an insertion loss less than 0.5 dB over this band.

The previous data on the circulator were taken with about 10 mW of CW power at the circulator's input port. Following these results, some high-power tests were run to determine the power level at which nonlinear behavior occurs in the ferrimagnetic material. A 2-watt CW source was connected to the circulator and no nonlinear behavior was observed. A pulsed magnetron source with a 0.001 duty cycle and 2.5 μs pulsewidth was connected to the circulator. At a peak power of 956 watts no nonlinearities were observed. Additional tests at higher power levels are necessary to determine the onset of nonlinear behavior.

These promising results encouraged additional work as to the feasibility of a latched microstrip junction circulator fabricated completely from a ferrimagnetic material. A latched circulator does not require an external dc magnetic field. Operation of the circulator is at the remanent magnetization of the ferrimagnetic material. A loop of wire positioned in the material is pulsed so that the enclosed magnetic material is magnetically saturated. The saturation magnetization falls to the remanent magnetization value (of the hysteresis loop for the material) when the pulse is turned off, if a closed magnetic flux path is provided, i.e., energy is not required for the formation of magnetic poles at surfaces with magnetic field discontinuities. If the pulse of opposite sign is applied, the remanent magnetization of the material is oppositely directed. The two remanent states of the material permit switching the direction of circulation in a circulator, thereby providing a method by which the device can be used as a switch or a digital nonreciprocal phase shifter.

Preliminary experiments on a latched two-piece microstrip junction circulator were initiated. Fig. 4 is a photograph of the configuration employed. The two ferrimagnetic pieces are shown on the left-hand side of the photograph, while the component on the right-hand side is the assembled unit. The white ring visible in the part at the far left is an annulus 0.025 inch thick which is filled with a low-loss dielectric material whose dielectric constant

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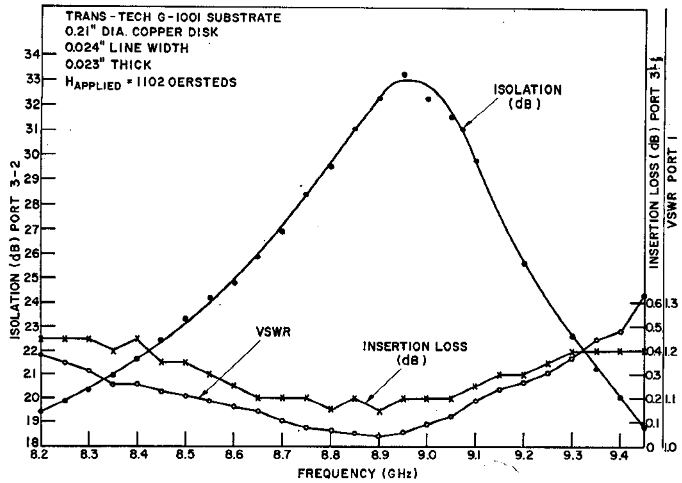

Fig. 2. Ferrimagnetic substrate microstrip junction circulator characteristics (electromagnet).

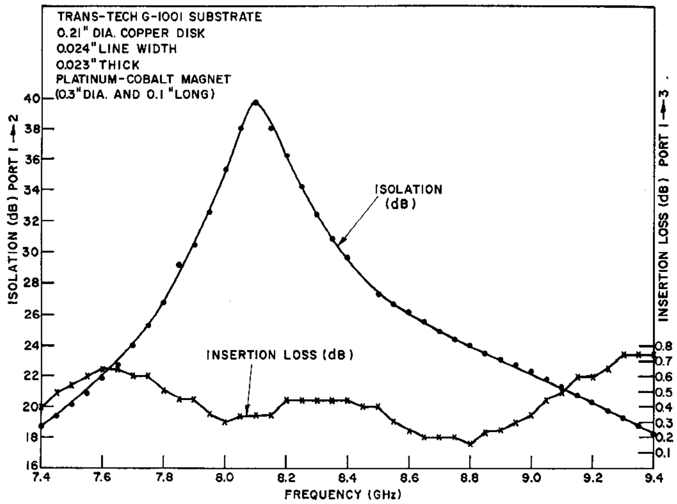

Fig. 3. Ferrimagnetic substrate microstrip junction circulator characteristics (permanent magnet).

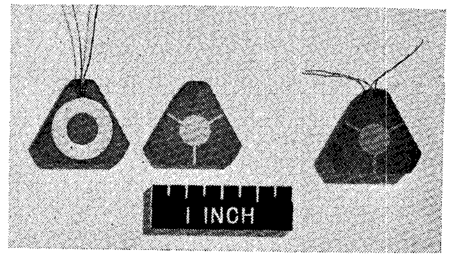

Fig. 4. Photograph of a two-piece latched microstrip junction circulator. (Right side of photograph is assembled circulator.)

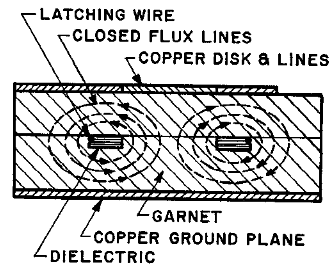

Fig. 5. Schematic cross-sectional view of latched circulator.

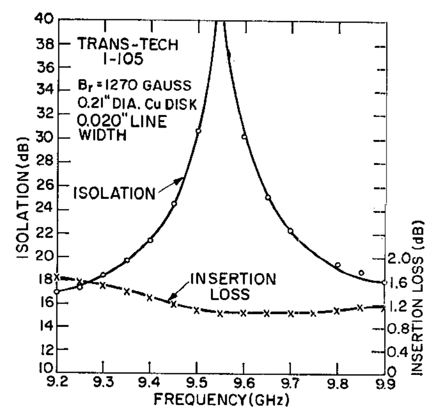

Fig. 6. Two-piece latched microstrip junction circulator characteristics.

matches the ferrimagnetic material. The dielectric is strictly for convenience because it eliminates the need to modify the quarter-wave linewidths for a proper impedance match in the annular region. A small lip on the underside of the dielectric holds the loop of wires used for the current pulse. Fig. 5 is a schematic cross-sectional view of the latched circulator showing the closed flux paths in the medium. Measurements of the latching energy required gave 0.8 μJ. This value is of the order of the experimental error. However, it is safe to assume that only a "few" microjoules of latching energy are required.

The preliminary experimental results established the feasibility of a latched microstrip junction circulator. Fig. 6 is a graph of the data obtained. A 350 MHz bandwidth for 20 dB isolation was measured, with an insertion loss varying from 1.15 to 1.3 dB over the band. This loss is considerably higher than that obtained with the thin ferrimagnetic substrates and small permanent magnets. Some of the difficulty lies in the thickness of the latched circulator. Its height was greater than a quarter of a guide wavelength and radiation was detected. A reduction in the circulator thickness reduced the insertion loss to 0.8 dB. There was still some radiation loss but this could only account for about 0.1 dB of the loss. The additional loss does not arise from operation at remanence because the loss was unchanged when the ferrimagnetic circulator was magnetically saturated in a uniform magnetic field. It is not obvious that the present geometry can give rise to low k-value (inverse wavelength) spin-wave excitation in the spin-wave manifold. However, this does remain as a possible explanation for the loss. The nature of this increased loss is under investigation at the present time.

These preliminary results were sufficiently encouraging to warrant an investigation as to the prospects for a one-piece latched circulator. The approach is almost identical with the RCA laminated memory sheet process[4] which uses the "doctor blading" technique to prepare sheets of sintered ferrimagnetic material which are then pressed together in a die. The latching wire is embedded in the center of the ferrimagnetic material layers by using a die to emboss a loop in the center of the laminated sheets. A platinum–sugar mixture adjusted for the shrinkage of the ferrimagnetic material is placed in the embossed region. The remaining sheets are placed on top, pressed, and fired. The resultant ferrimagnetic material is uniform and isotropic with no evidence of laminations and contains the platinum loop of wire for latching. Sheets 12 by 4 inches can be fabricated with wire loops in place. Evaporation of copper disks, lines, and ground plane then provide a sheet of latched circulators which can be cut off into individual circulators or hooked together via evaporation of connecting lines to form a large number of switchable circulators. It is possible to modify the copper disk shape[5] so as to construct a multibit digital nonreciprocal phase shifter for phased array systems.

The first one-piece latched microstrip junction circulator was identical in appearance with the photograph of the composite two-piece latched circulators shown on the far right side of Fig. 4. The platinum–sugar mixture was not used because an embossed die of the desired shape was not available. A 0.010 inch loop of platinum wire was placed on the sheets in the die and the remaining sheets were placed on top and pressed. After the final firing, evidence of shrinkage effects were observed as cracks in the vicinity of the platinum wire emerging from the specimen. Nevertheless, the experimental results established feasibility and, while far from outstanding, did substantiate the fact that the approach warrants further effort. The maximum isolation was 12 dB with a 10 dB isolation bandwidth of 350 MHz. The insertion loss was high, ranging from 2.0 to 5.0 dB over the band. However, a number of factors can account for this loss. The specimen was thicker than a quarter of a guide wavelength and the associated radiation loss was evident. The cracks in the material also contribute to the insertion loss. Furthermore, a thin specimen of the laminated ferrimagnetic material was prepared with size and shape identical with that shown in Fig. 1. This circulator was tested in an electromagnet where it showed a high insertion loss. The ferrimagnetic material was yttrium–iron–garnet, and it was a poor microwave material when compared to the commercially available materials. In all fairness it should be noted that this was the first attempt at RCA to prepare YIG material in laminated sheets since all previous experience has been with ferrite materials for laminated memory sheets. It is a reasonable assumption that a materials study would lead to materials comparable to commercially available material. However, before this is done, the insertion loss versus thickness problem previously discussed must be resolved. Following this, a laminated garnet materials study can be launched, or ferrite laminates could be used. The laminated technique is of significant importance because it provides an inexpensive means for batch fabrication of latched circulators. These circulators would find wide use as individual elements, or as inexpensive digital nonreciprocal phase shifters for phased array systems.[5]

This author's present work, and that of others at Syracuse University[6] where ferrimagnetic substrates have been used to build latched nonreciprocal devices, has established the role of these devices in microwave integrated circuits. Recent work at RCA Laboratories on new magnetic materials, chalcogenides,[7] has expanded this prospective role. Ferromagnetic insulators which can be locally doped to yield semiconductor materials with high mobilities and high carrier densities have been developed. It may be possible to prepare substrates of these materials, dope them locally to provide active devices such as amplifiers and oscillators, and then use the undoped portion of the substrate for passive nonreciprocal (and reciprocal) devices. Operation latched or with a permanent magnet should be feasible. These advances with both materials and devices make the prospect of microwave systems on magnetic substrates a distinct possibility.

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High-Dielectric Substrates for Microwave Hybrid Integrated Circuitry

***Abstract*—Microstrip transmission-line parameters of temperature-compensated titanium dioxide have been measured. This material has a dielectric constant ranging from 25 to 100. The variations of microstrip wavelength, characteristic impedance, and attenuation with geometry and dielectric constant are in good agreement with the theory. This material is particularly attractive for microwave circuits because of the short guide wavelength and low attenuation.**

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INTRODUCTION

Microstrip transmission-line components are finding wide application in microwave integrated circuits. Properties of the microstrip structure have previously been investigated for semiconductor dielectrics,[1] low-dielectric $k<10$ ceramics,[2] sapphire,[3] and Polyguide.[3] This correspondence will present the properties of high-dielectric $k>10$ substrates in the microstrip configuration.

All of the data were taken from the AlSiMag temperature-compensating series No. T96 manufactured by American Lava Corporation. The dielectric constant of this material is in the range of 25 to 100, and the material itself consists of titanium dioxide with additions of magnesium and titanium to provide a minimum change of capacitance as a function of temperature.

The primary virtue of high-dielectric substrates for microwave circuits is reduced size. By increasing the substrate dielectric constant from 10 to 100 the guide wavelength of a 50 ohm microstrip line can be reduced by a factor of 0.35. Since the high-dielectric microstrip lines also have low loss and a useful range of impedances, this class of circuits will undoubtedly find wide application in microwave integrated circuitry.

CHARACTERIZATION OF MICROSTRIP TRANSMISSION LINES

Three properties are required in characterizing microstrip lines: wavelength, characteristic impedance, and attenuation. The wavelength in the microstrip line has been measured by two methods. Using the first method, the line is operated as a half-wavelength filter which is loosely coupled and open circuited at both ends. By measuring the resonant frequencies of the filter the wavelength in the microstrip line may be simply calculated.

An alternative method consists of short circuiting the transmission line and searching for the frequencies where the VSWR minimum positions are identical with those of a short-circuited air line. At these resonant frequencies the line is once again a half-wavelength filter. Better measurement accuracy seems to be obtained from the second method, although both methods give the same value of guide wavelength.

Characteristic impedance may be simply determined from time-domain reflectometer measurements. With the line terminated in 50 ohms, the reflection coefficient is measured for a transmission line which is sufficiently long for transitions at the end of the line to have a negligible effect.

The attenuation of the line may be determined by measuring the loss tangent of the short-circuited resonant line. This loss may be expressed in dB/cm or dB/λ_g. Using the latter units, the advantages of high-dielectric substrates will become more apparent.

MEASURED PERFORMANCE

The measured and calculated ratio of free-space wavelength to microstrip wavelength is plotted in Fig. 1 as a function of dielectric constant and geometry. This ratio has been