# A COMPACT BROADBAND MICROSTRIP CIRCULATOR FOR PHASED ARRAY ANTENNA MODULES*

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## ABSTRACT

Minimal size, weight and cost are three requirements for circulators to be packaged in T/R modules. This paper describes circulators realized under these constraints. Hybrid fabrication methods are used, in order to meet magnetic biasing and shielding requirements.

## INTRODUCTION

Active phased-array antennas generally require gyromagnetic (ferrite) and semiconductor devices. Fundamental differences in their materials and material processing techniques make monolithic integration of these two types of devices extremely difficult. Ferrite components are also unique in that most require a dc magnetic bias field, which then requires shielding to prevent interaction between adjacent components.

The circulators to be described are thought to be near the ultimate in miniaturization for the level of performance achieved over the 6-18 GHz frequency band. Advances in microelectronics packaging of the three-port circulator have been made by reducing overall size to 0.600 x 0.275 x 0.090 inch. The general concept for incorporating these units in modules is illustrated in Figure 1. The preferred terminals and terminal locations are the microstrip line interfaces as drawn. To allow inline conductor connections to adjacent circuitry and to provide for a yoke enclosure around the device, a recess in the module floor level is required.

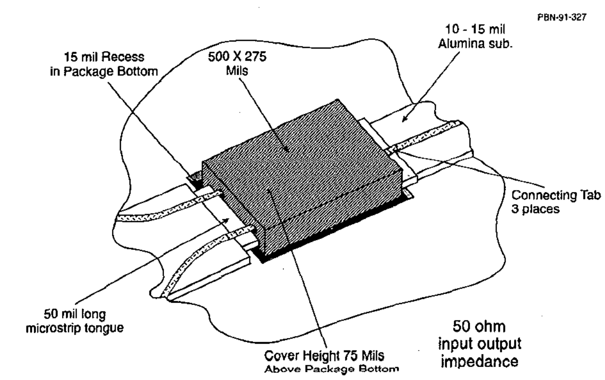


*Figure 1.* *MMIC-Compatible, Broadband Circulator.*

Standard aluminum impregnated SiC module boxes, incorporating the required bottom recess, were obtained in order to demonstrate the validity of this packaging approach.

## IMPEDANCE MATCHING

The electrical design approach was, first, to consider the broadband match to a lower than 50 ohm resistor with conductor elements realizable within the confines of the allowable space and using the available substrate materials. The degree to which this can be accomplished determines, to a large extent, a miniature circulator's performance.

Data for Tchebyscheff quarter wave impedance matching transformers showing return loss for a given bandwith, impedance ratio and number of sections was used to obtain a global view of design possibilities. Subsequent, refined design procedures in this area involved modifying the Tchebyscheff response for transformer connection to a less than ideal resistive termination as afforded by the circulator junction.

Theoretical improvements in performance with additional transformer elements are, in practice, offset by increased insertion loss and, due to large bandwith, insertion loss slope. Realistically, a decision to use three or four sections is required. A circulator conductor pattern with three-section transformers was conveniently accommodated within the allocated space for substrates with dielectric constants of 13 or larger.

Figure 2 is the impedance plot for a typical three-section transformer used to terminate the circulator junction.

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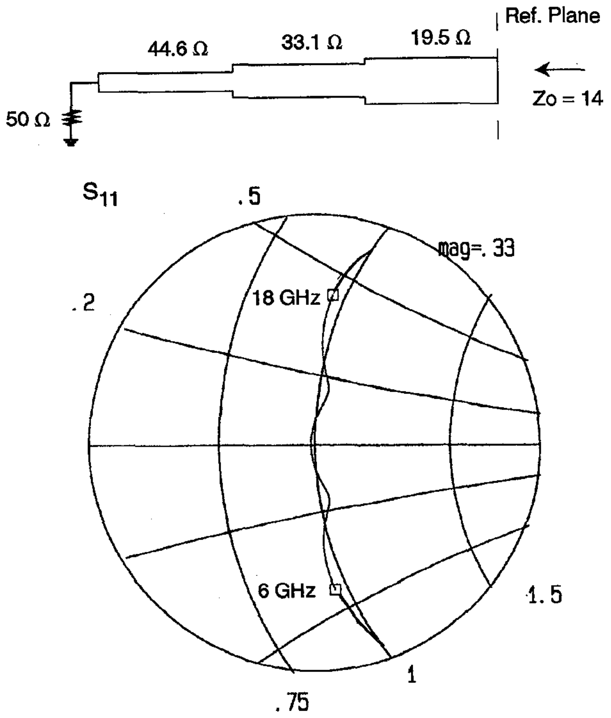


*Figure 2. Transformer Design and Reflection Coefficient Plotted on a Smith Chart.*

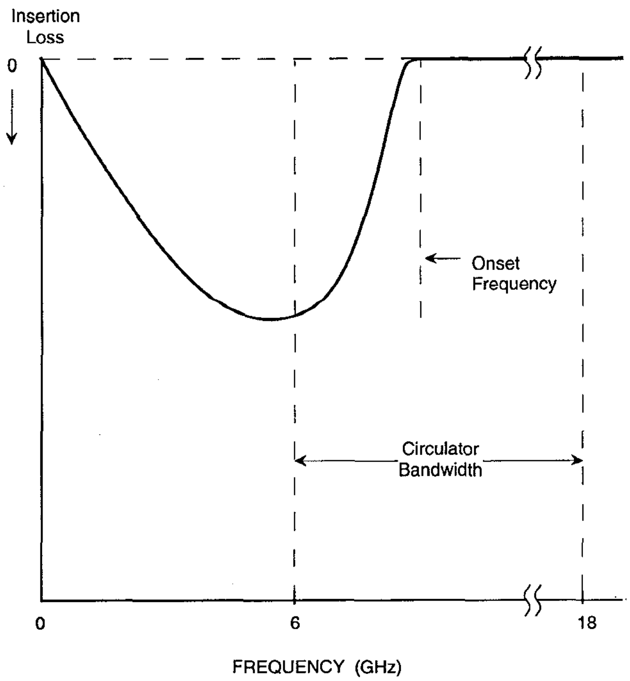


*Figure 3. Low Field Loss Curve for an Unbiased Ferrite - Saturation Magnetization = 3000G - Onset Frequency = 8.7 GHz.*

## COMPOSITE SUBSTRATES

It is well known that relatively broadband circulator performance can be realized with a microstrip design on a uniform ferrite substrate or on a composite substrate consisting of ferrite and a dielectric material. However, for the very large bandwidth required in the present project (6 to 18 GHz), a more complex composite substrate, consisting of three materials, has been found to be advantageous.

The high saturation magnetization ferrites ($4\pi Ms$ = 3000 Gauss), required for these bandwidths, exhibit inband "low field loss" in the unbiased state (Figure 3). Optimum external dc biasing of the ferrite lowers the "onset" frequency at which this loss occurs. The field within the ferrite is not uniform, i.e., spatially constant, due to the shape-dependent demagnetizing field.[1,2]

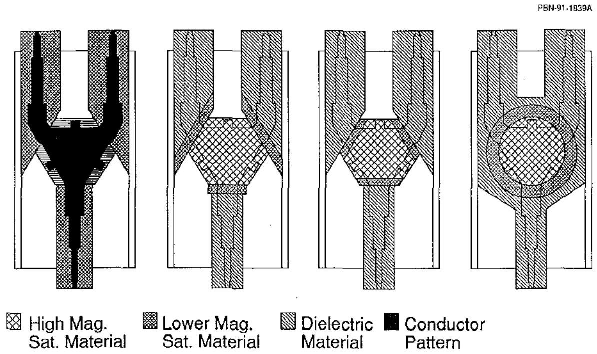


*Figure 4. Circulator Substrate Arrangements under Evaluation.*

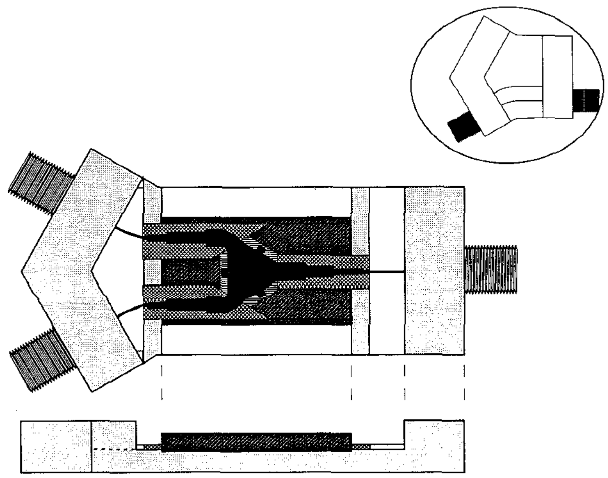

*Figure 5. Circulator in Test Fixture. Upper right shows modified fixture used for deembedding.*

Substrate sections of a second ferrite material with a lower saturation magnetization were used to improve this situation and further lower the onset frequency. In Figure 4, these can be seen in an arrangement bordering the primary ferrite core.

For these electrical reasons, circulator microstrip substrates were a composite of two and three materials. Two fabrication techniques were explored for cost comparison: (1) a base plate assembly of ribbon bonded, conductor patterned, subsections cut from different wafers, and (2) an assembled composite single substrate with parts epoxy cemented, which was then metalized, patterned, and base plate mounted.

Some of the substrate geometric permutations used for performance evaluation are shown in Figure 4. The first three are examples of patterned substrates fitted and aligned in a U shape yoke section. The fourth is a geometry with captivated parts that are more easily fitted.

## CIRCULATOR JUNCTION

Boundary conditions for the circulator resonator are defined by the triangular shaped conductor pattern realized on a larger ferrite surface. Its shape can be hexagonal or circular, the choice depending on convenience of fabrication. Since the resonators were on 10 and 15 mil thickness substrates, the RF fringe fields associated with the resonant mode are spatially localized within the central ferrite disc and do not reach the ferrite boundaries in any intensity.

In experiments, the dc field used to bias the junction for optimum low frequency insertion loss was found to be less than that required for best overall circulator performance, which then occurred for a slightly reduced bandwith, shifted in frequency.

Junction impedance was determined from experiments by analyzing modifications similarly made to transformer sections of all three arms. This work was performed with circulators configured wye symmetric and with substrates mounted in a conventional test fixture.

## HOUSING YOKE

The yoke is required to confine the magnetic bias field to the interior of the circulator and to reduce magnet size. Its electrical effect is similar to that of a waveguide section, which is beyond cutoff and open at the ends. The waveguide section is dielectrically loaded to the extent required to support the microstrip circuitry. The dielectric loading is kept to a minimum, thereby minimizing the possibilities for spurious resonance responses.

With this housing and the pattern of substrates, a high order resonance associated with the junction dimensions was troublesome if entertained too close to the band edge. To minimize the yoke's adverse detuning effect, upon this resonance a W/G short was required within the enclosure.

A housing is now used where the plane of this short is a wall section. The result is a smaller yoke with more transformer line substrate exposure.

The realizable reduction in circulator height is, in no small measure, due to the high energy SmCo magnet. The magnet (nominal 20 mil thickness) was attached to the yoke interior surface above the junction substrate.

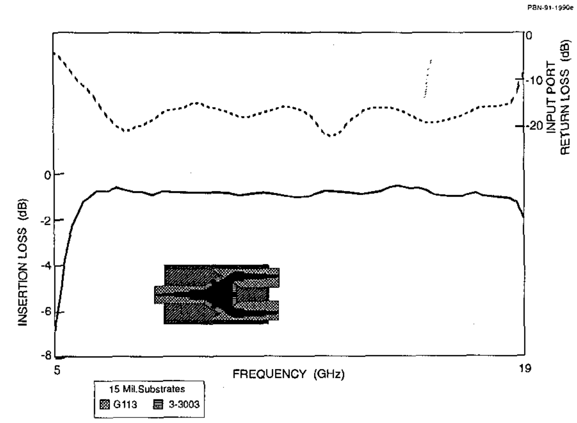


*Figure 6. MMIC-Compatible, Broadband Circulator Measured Performance.*

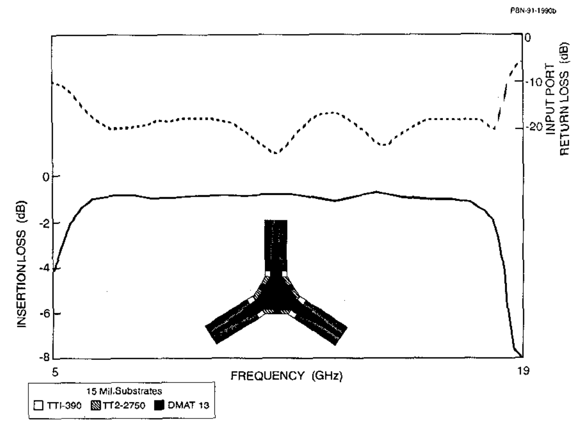


*Figure 7. Room Temperature Response for a Circulator on a Composite Substrate with a Nickel Ferrite at the Center.*

## FABRICATION TECHNIQUES

Each of the two fabrication techniques described above has a difficult step, as well as several, easy routine steps. For the circulator built with the single, composite substrate the most complex phase happens initially with the ceramist work: machining and close tolerance fitting and cementing parts in a block, which is then sliced into substrates. The follow-on activity is then routine work.

For the circulator built by assembling several precision machined parts, the initial steps are easy and routine. The difficulty lies in maintaining close tolerances when the parts are bonded together.

## CIRCULATOR PERFORMANCE

The best room temperature performance to date was achieved with a circulator mounted in the test fixture shown in Figure 5. The circulator used a microstrip pattern formed on a composite substrate of two ferromagnetic materials. A Li-based ferrite was used for the resonator and transformer sections realized on YIG substrates. Performance parameters are shown in Figure 6.

Room temperature performance with a nickel ferrite core and a magnesium ferrite for the subsections, shown in Figure 7, was comparable to that of the circulator described above. The insertion loss was to a degree higher, and the low frequency response at room temperature not quite as good. However, performance at low temperatures was much better, attributable to the higher Curie temperature of the nickel ferrites. Impedance transformer sections were realized on DMAT 13 dielectric material for this circulator, and the circulator was measured in the wye configuration, rather than the rectangular configuration.

## CONCLUSION

The two fabrication techniques described above lead to substantially the same device performance. We believe that the technique based on single, composite substrates is preferable for large scale production, because the required skills are more readily available.

The use of microstrip (rather than stripline) in the design of this circulator is seen as the most cost-effective alternative, and has certainly provided the means for effective and speedy design iterations.

## ACKNOWLEDGEMENT

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[1] R.E. Blight and E. Schloemann, Paper KB-01 at 1992 Intermag Conference.

[2] E. Schloemann, Paper KB-04 at 1992 Intermag Conference.

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