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LOW LOSS 92-100 GHz CIRCULATORS

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A broadband W-band circulator is described that achieves 0.5 dB insertion loss over the frequency range from 92.5 to 100.6 GHz. The large bandwidth improvement results from using *two* higher propagating modes.

Introduction

This paper describes the development of rugged, wideband waveguide circulators operating in the 90 to 100 GHz frequency range. The work performed under this task includes:

- The development of analytical methods for the design of circulator junctions employing existing ferrites with saturation magnetization known to be too low to use with previous design methods
- Experimental verification of these methods
- Fabrication of deliverable components

Among key considerations during this development were the aspects of repeatability, producibility and environmental performance.

Considerable experience with designs at lower microwave frequencies clearly identified the inadequate level of saturation magnetization ($4\pi M_S$) of presently available ferrite materials for obtaining wideband and low loss performance.[1] The present highest level of saturation magnetization, about 5000 gauss, is adequate to about 50 GHz for junction designs supporting propagation of the lowest order modes. Based on previous circulator designs, the desirable value of the saturation magnetization at 94 GHz approaches 10,000 gauss - an unrealistic value considering existing materials. For designs at higher frequencies, new and improved design techniques were necessary, since significant near term advances in ferrite materials technology could not be expected. These new analytic design techniques were developed and, in addition to excellent performance of the completed circulators (Figures 1 and 2), were instrumental in identifying future methods for simpler and easier modifications of ferrite materials.

In addition to the improvements necessary for constructing a W-band circulator, several other design improvements affecting lower frequency designs were established. Among them were better characterization and an optimized selection of materials for given frequency requirements, improved determination of junction proportions to achieve balance and equal amplitude of the circulator VSWR and isolation ripple, and a method for the unique solution of junction ferrite dimensions for a given required bandwidth.

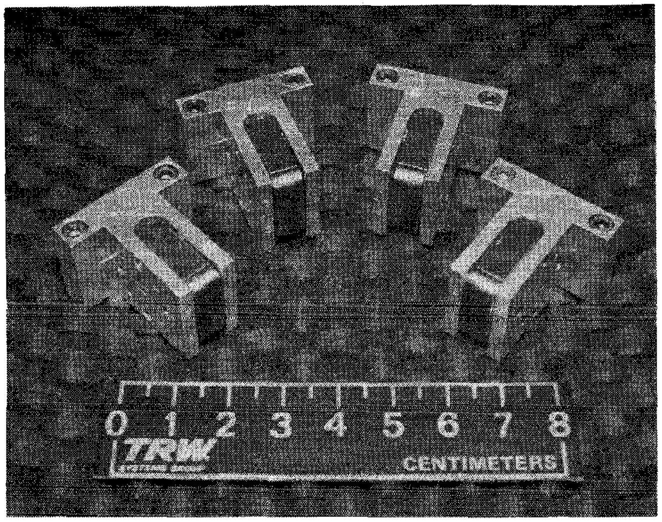

Figure 1. W-Band Circulators

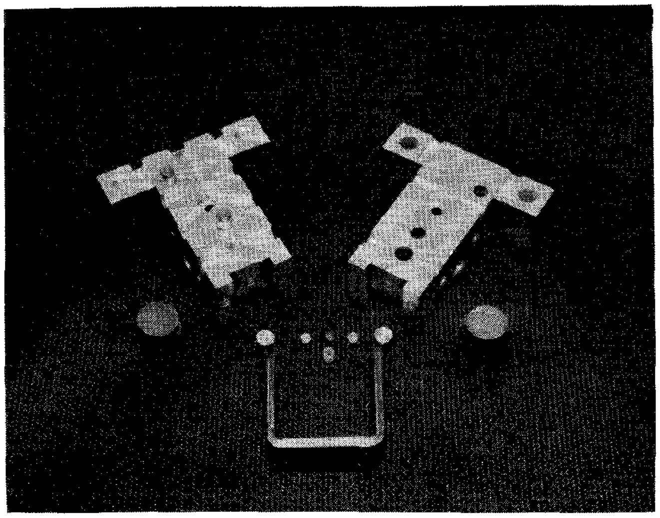

Figure 2. Disassembled W-Band Circulators Showing Details of Housing Construction and Junction Parts

Design Considerations

The requirement of a high saturation magnetization material greatly limits the field of acceptable material. To reduce junction loss the ferrite requirements include low loss tangent and narrow line width. Our choice of ferrite is a high density nickel-zinc composition with $4\pi M_S$ = 5250 gauss and ε_r = 13, manufactured by Countiss Industries. The symmetrical junction is comprised of a single turnstile half-wave long C-48 ferrite. The construction of the junction is presented in Figure 3. We observe the right circular cylindrical ferrite supported on either end with dielectric spacers which also serve as in-line impedance matching. The junction components are then contained inside a dielectric tube which is securely indexed to a quarter wave long impedance transformer. As a resonator, the junction ferrite permits the propagation of higher order modes, proportional to 3.054 and 3.832 Bessel function roots. This results in an increased junction volume and the present insertion loss of about 0.5 dB with a ferrite having the dielectric constant $\varepsilon_r = 13$. A further expansion of the present 8 GHz bandwidth and a reduction of the insertion loss is possible when ferrites with improved physical properties become available. From the beginning of this development, a strong emphasis was placed on wideband performance. This is a component characteristic which is desirable not only for electrical reasons but is crucial to producibility, especially with millimeter wave components where the waveguide and junction parts are relatively small.

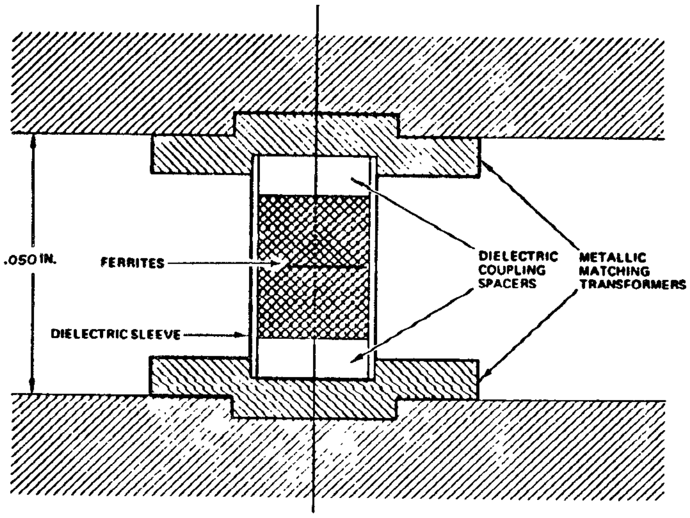

Figure 3. Physical Arrangement of Broadband Waveguide Circulator Junction

Narrowband components even in larger waveguides require tighter tolerances to assure acceptable repeatability. In waveguides smaller than WR-15, components with about 1 GHz of bandwidth are simply not producible with ordinary machine-shop methods and tolerances. Having producibility as one of the requirements of this development, in addition to the problems resulting from inadequate magnetic characteristics of the ferrite materials, we explored several junction design concepts and approaches to provide wideband performance. These efforts included characterization of the ferrites to determine the optimum selection of materials for given requirements. We also evaluated various junction configurations, such as assemblies of quarter-wave and half-wavelength ferrite and performed an extensive analytical and experimental evaluation of the effects of the junction ferrite properties on the bandwidth and insertion loss of the circulator.

The choice of cylindrical geometry was established as a basic approach because this geometry, in comparison to others, combines the simplicity of mathematical analysis with economical manufacturing. An analytically deterministic design permits relatively easy calculation of the optimum dimensions of the junction parts. These simple shapes are then easily fabricated, inspected and assembled, using standard machine shop machinery and production methods. The finished product is producible, repeatable and has highly reliable electrical and environmental performance.

Originally, the design concept of a cylindrical turnstile junction was proposed and explained in 1970 by Owen.[2,3] Later, Helszajn[4-7] proposed the treatment of the junction ferrites as dielectric resonators and in several papers presented practical and useful analytic design data.

The present design extends previous efforts[1] to higher millimeter wave regions, where the characteristics of presently available materials preclude wideband, producible designs with the junction supporting the propagation of the lowest order modes. A significant fourfold increase of the operating bandwidth is possible and was achieved through the design of the junction ferrites propagating properly selected higher order modes. This leads to larger bandwidth, but as the consequence of a larger ferrite volume, the insertion loss is increased to about 0.5 dB.

The end result, the final component performance, is obtained through analytic correlation of the magnetic, dielectric and transmission line properties.

The frequency response of the circulator and the dimensions of the junction ferrites are controlled and determined by the dielectric properties of the ferrite. The propagation modes and ferrite proportions are obtained from the propagation characteristics of cylindrical dielectric resonators depicted in graphical form in Figure 4. The parameter X_{1m} is the root of J_1 or J_1' defining the TM or TE mode of operation, respectively.

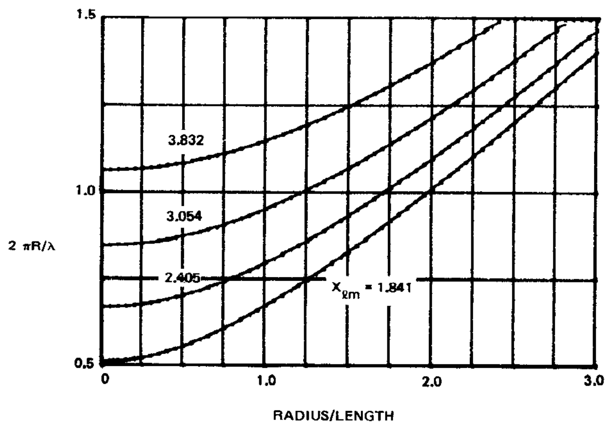

Figure 4. Ferrite Dielectric Modes

The junction is impedance matched to the standard 3-port waveguide housing following the method suggested by E.J. Denlinger.[8]

Figure 5 shows typical swept frequency responses, VSWR, isolation and insertion loss of the circulators depicted in Figure 1.

Summary of Results

Six circulators were produced with the following typical performance:

Center Frequency:	96 GHz
Insertion Loss:	0.5 dB over 7 GHz of Bandwidth, 1 dB over 9 GHz of Bandwidth
Isolation:	>20 dB over 6 GHz, >15 dB over 8 GHz
VSWR:	<1.3:1 over 6 GHz, <1.5:1 over 8 GHz

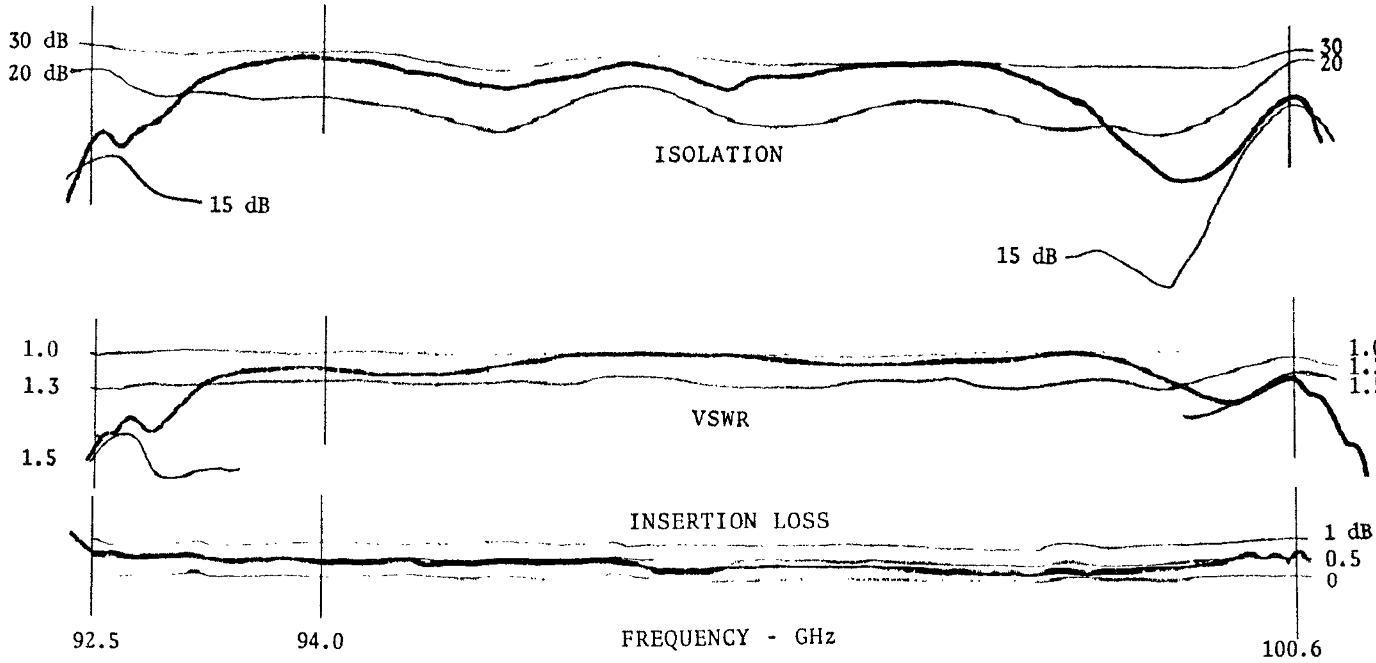

Figure 5. Typical Performance Characteristics of W-Band Circulators

Conclusions

The design for a producible, wideband waveguide junction circulator operating in the 90 to 100 GHz frequency range was established. A four-fold improvement in operating bandwidth over previous designs was achieved. The wide operating bandwidth permits better producibility and a high degree of repeatable performance with a wide range of mechanical tolerances. This performance was obtained through advances in design methods that permitted the use of materials generally considered inadequate for frequencies above 50 GHz.

Improvements in analytical methods were not only indispensable to performing this task, but also constitute a significant contribution to state-of-the-art ferrite component design for all lower frequency ranges. These new design concepts facilitate a more disciplined selection of materials with optimum characteristics for given requirements and permit accurate calculations of junction dimensions, which produce balanced, symmetrical, equal amplitude response in isolation and VSWR ripple and wideband low insertion loss performance. The validity of these improvements was confirmed through component designs with excellent performance at several lower frequencies.

References

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