LOW LOSS BROADBAND EHF CIRCULATOR

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Abstract

A new approach to waveguide circulator design is reported that has resulted in a totally rugged, temperature stable circulator with exceptional RF performance. With this design, insertion loss of less than 0.1 dB, isolation more than 20 dB and VSWR less than 1.2:1 has been achieved, each over 7 GHz of bandwidth from 27 to 34 GHz and 31 to 38 GHz.

Introduction

The high performance design[1] reported here has been developed from a reduced height (approximately half of standard height) waveguide design employing one single ferrite. Contrary to an opinion expressed in the excellent recent paper by Helszajn and Tan[2] which suggests superiority of the single-disk geometry over multi-ferrite arrangements, significant improvement in circulator performance was obtained with a two-ferrite/septum design. Excellent control over the key parameters has been achieved to a point where the design has been shown to be scalable to (and yield high performance over) any 20 to 25% frequency band in the 12 to 40 GHz range.

The novel standard height waveguide design optimally combines RF broadband and low loss performance, parts simplicity, ruggedization and temperature stability in one unit. Specifically,

a) No epoxies or adhesives of any kind are used since all cylindrical parts are self-indexing. The result is a rugged mechanical design directly suitable for space applications.

b) Total temperature stability of the design; even 2:1 variations in the magnetic biasing field strength have no measurable effect on circulator performance.

c) A thin metallic septum separates two symmetrically located ferrite discs. This approach allows the use of standard height waveguide.

Design Approach

As part of preliminary circulator design, the diameter and length of ferrite and dc magnetic field for circulator action was determined as shown below. This satisfies the required boundary conditions for the two circularly polarized eigen excitations which propagate in rotating modes internal to the ferrite (each of these experiences a different effective permeability, with the propagation constants directly but nonidentically influenced by the external magnetic biasing field), and an in-phase dielectric resonator mode. For circulator action, a $2\pi/3$ phase difference is required between the rotating modes and the in-phase coaxial mode. In order to achieve good bandwidth, it is paramount to employ the lowest possible mode and shortest associated path length since a longer path length difference results in a narrow circulator bandwidth because the rate of phase changes with frequency of the in-phase mode is much less than that of the rotating mode. Widest bandwidth is obtained by fine tuning the dimensions to achieve equal ripple Chebychev response characteristics.

Low loss dielectric is used to sandwich the ferrite to provide for coupling into and out of the TT2-111 ferrite. The length of this dielectric is selected so as to center the in-phase dielectric mode at the center frequency. The lowest order resonance condition is found from

$$\frac{\pi D_{eff}}{\lambda_o} (\varepsilon_{eff})^{1/2} = 1.84 \qquad (1)$$

D_{eff} = 1.1 X diameter of ferrite

ε_{eff} = unknown effective dielectric constant of matching dielectric

λ_o = free space wavelength.

The length of the coupling dielectrics is found from the relationship

$$\frac{\ell_d}{\ell_f} = \frac{1 - \frac{\varepsilon_{eff}}{\varepsilon_f}}{\frac{\varepsilon_{eff}}{\varepsilon_d} - 1} \qquad (2)$$

In this equation,

ℓ_d = length of matching dielectric

ℓ_f = length of ferrite

ε_{eff} = effective dielectric constant, determined from equation (1)

ε_f = dielectric constant of ferrite

ε_d = dielectric constant of matching dielectric

Additional key design considerations affect the design of the metallic matching transformer external to the ferrite. The diameter of this transformer is equal to the diameter of the ferrite plus $\lambda_o/2$. The height of the transformer is optimized experimentally for best performance. Care must be taken not to exceed a critical step height since this will introduce spurious resonances.

Mechanical ruggedness is achieved by stacking the five cylindrical piece parts (septum, two ferrites and two dielectric coupling spacers) inside a thin dielectric sleeve. The sleeve is indexed to the housing via a recess in the metallic matching transformers, as clearly seen in Figure 1. This arrangement obviates the need for epoxies or glues and additionally assures low loss. A photograph of an assembled Ka-band circulator is shown as Figure 2.

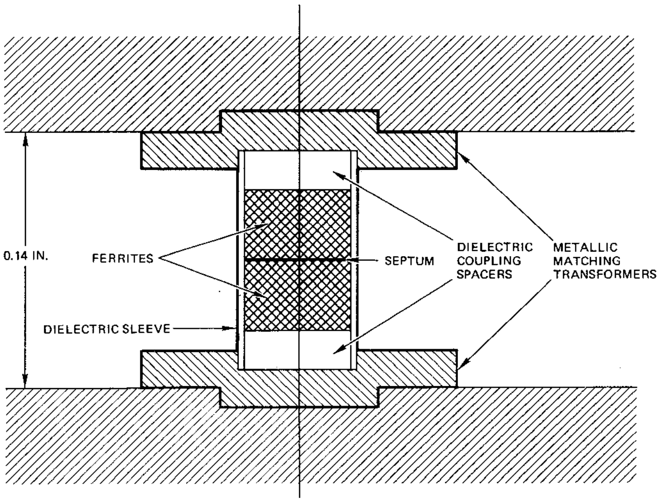

Figure 1. Physical Arrangement of Broadband Waveguide Circulator Junction

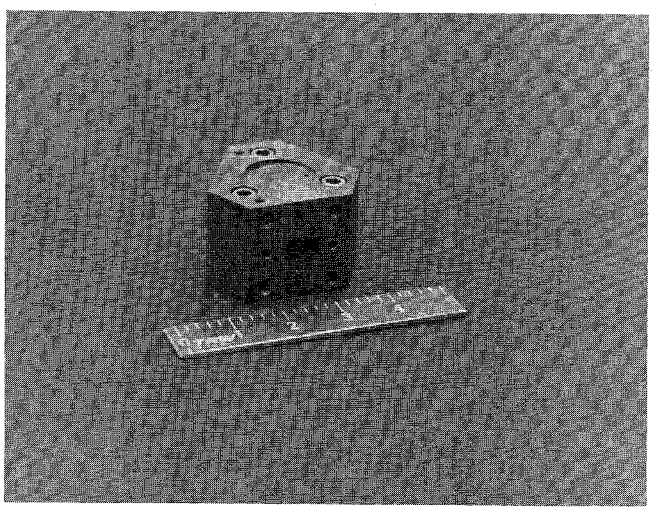

Figure 2. Ka-Band High Performance Circulator

Once the required magnetic field for circulation is established in the junction, significant increases of the magnetic field strength produce only minor changes in circulator performance. Minor shifts occur only at the outer edges of the band. Fluctuations of performance caused by temperature changes are minimized since the junctions are biased by approximately twice the required magnetic field for acceptable circulator performance. This characteristic of the circulator junction presents a significant advantage over designs requiring accurate adjustment of magnetic field and where increasing or decreasing the magnetic field causes severe frequency shifts and degradation of performance. Rare-earth, high energy permanent magnets are used because their reversible loss in induction and coercivity varies such a small amount, e.g., from +0.033% at -100°C to -0.048% at +250°C. Such small changes will not produce any measurable changes in circulator performance.

Experimental Results

Results typical of the standard height dual ferrite/septum type circulator design achieved are shown in Figure 3. The exceptionally low loss typical of this broadband design is primarily due to (1) exceptional match of the junction geometry, and (2) absence of epoxies or adhesives. As seen from Figure 3, the VSWR is less than 1.1:1 over 4 GHz.

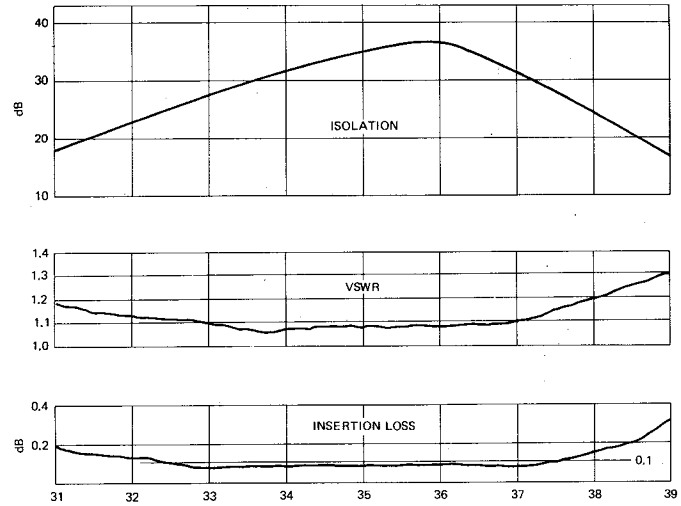

Figure 3. Typical Circulator Performance (Standard Height Waveguide, Septum Type)

Once determined, the basic design was utilized in several ways. First, the design was scaled to achieve wideband circulator performance in the lower part of Ka-band. The broadband results achieved are shown in Figure 4. The quality of the basic design and level of parameter control was verified by successfully demonstrating broadband circulator performance at Ku-band. Further validity of the design was established by utilizing the basic design in the development of several four- and five-junction circulators. No interstage matching was required between successive junctions.

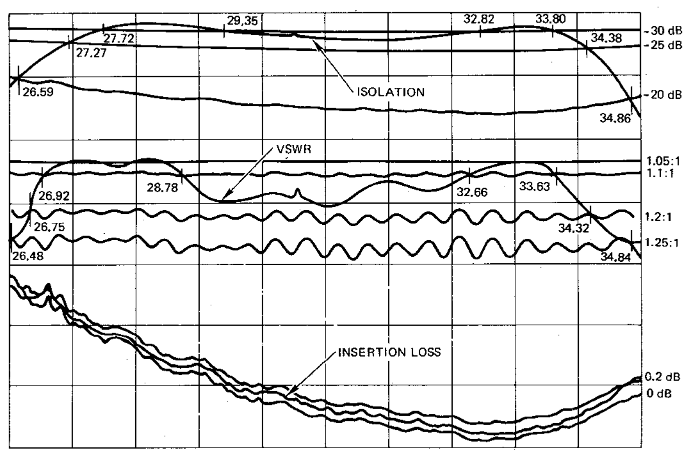

Figure 4. Isolation, VSWR, and Insertion Loss of 26.5 to 34 GHz Circulator

The hardware derived from the basic design is depicted in Figure 5; a summary of the circulator performance achieved is presented in Table 1.

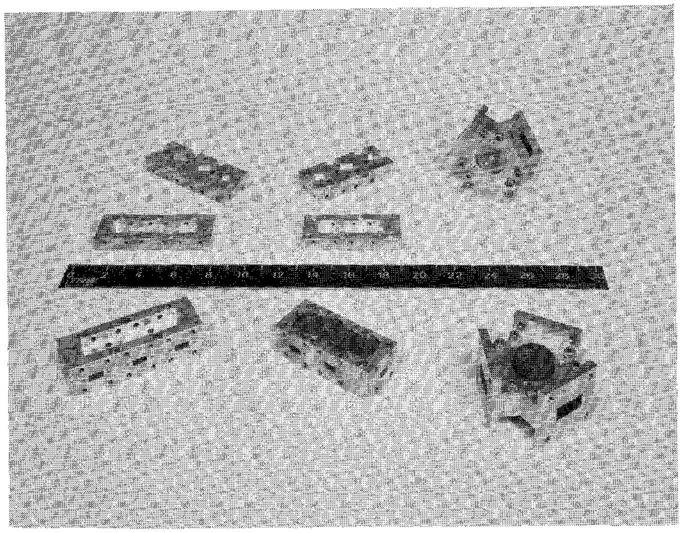

Figure 5. Hardware derived from basic design includes four- and five-junction Ka-band circulator (center and left foreground) and Ku-band circulator (right).

Table 1. Summary of Circulator Performance Achieved

Component	Parameter	Performance
Ka-Band Circulator 31 - 38 GHz	Insertion Loss Isolation VSWR	<0.1 dB >20 dB <1.2:1
Ka-Band Circulator 26.5 - 34 GHz	Insertion Loss Isolation VSWR	<0.1 dB <20 dB <1.2:1
Five-Junction Circulator 31 - 38 GHz	1-Pass Insertion Loss 3-Pass Insertion Loss Isolation per Pass Input, Output VSWR	<0.1 dB <0.4 dB >20 dB <1.2:1
Ku-Band Circulator*	0.2 dB Insertion Loss BW 20 dB Isolation BW 1.2:1 VSWR Bandwidth	13.5 - 17 GHz 12.6 - 18 GHz 13.6 - 17 GHz

*scaled from 31 - 38 GHz basic design

Summary

In summary, the design approach and experimental results have been presented describing a rugged temperature stable high performance circulator design that has proved to be scalable. These circulators are being successfully utilized in the development of broadband solid state amplifiers.

References

1. Patent applied for.
2. J. Helszajn and F. C. Tan, "Design Data for Radial-Waveguide Circulators Using Partial-Height Ferrite Resonators," Vol. MTT-23, March 1975, p. 288.