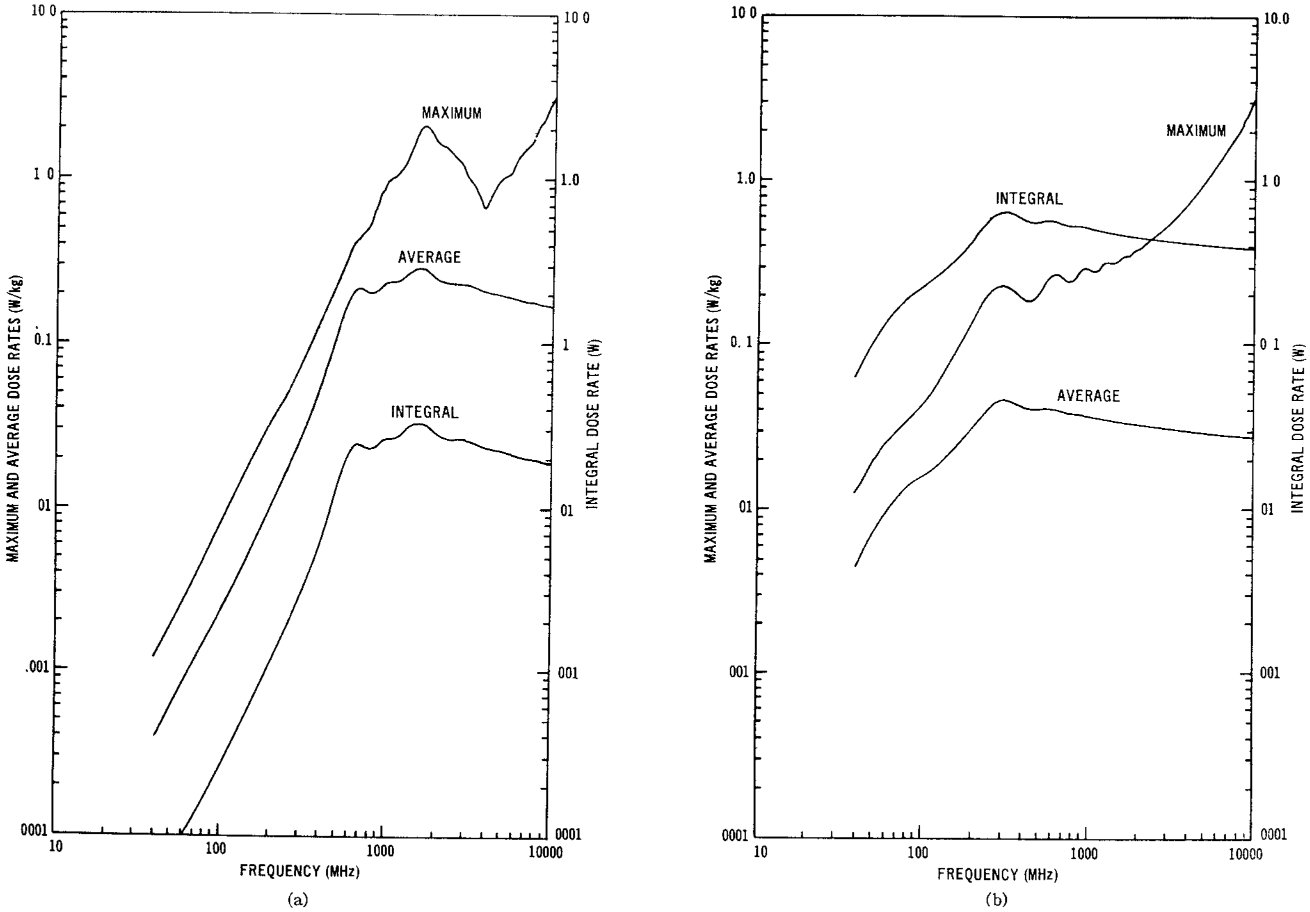

Fig. 7. Frequency dependencies of maximum, average, and integral dose rates in muscle equivalent spheres of (a) 3-cm and (b) 15-cm radii for incident monochromatic plane waves with exposure rate of 1 mW/cm².

where

$$\beta = \{\omega^2\mu\epsilon - (\pi/a)^2\}^{1/2}$$
$$Z_0 = [\{\epsilon/\mu\}\{1 - (\lambda/2a)^2\}]^{-1/2}$$
$$E_+ = (4P_f Z_0/ab)^{1/2}$$
$$\dot{X}_0 = 2P_f/ab$$

P_f forward power into the waveguide

λ wavelength

μ, ϵ permeability, permittivity

ω $= 2\pi f$

f source frequency.

The preceding are exposure conditions of a waveguide operating in TE_{10} mode (with matched load and in the absence of the animal).

Acknowledgment

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High-Power *S*-Band Junction Circulator

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***Abstract*—The design of a high-power air-cooled microwave Y-junction circulator which is capable of operation at peak and average power levels of 800 kW and 800 W, respectively, is described. The unit is an *H*-plane waveguide circulator which is externally air cooled. The circulator design employs a full-height substituted YIG rod with a center metal pin together with boron nitride matching transformers.**

The circulator exhibits an insertion loss of less than 0.4 dB, isolation greater than 22 dB, and a VSWR < 1.26:1 over a 400-MHz bandwidth centered at 3.3 GHz. At high-power levels, the device exhibits insertion loss of less than 0.9 dB, isolation greater than 20 dB, and VSWR < 1.25:1 at an indicative frequency within the operating bandwidth.

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Introduction

This short paper describes the development of an air-cooled high-power S-band Y-junction circulator. The H-plane circulator discussed is reasonably compact and lightweight, and the bandwidth is greater than 13 percent. Insertion loss is less than 0.9 dB, and isolation greater than 20 dB with VSWR < 1.25:1.

The Y-junction circulator employs a gyromagnetic rod bearing a metallic center pin and boron nitride transformers in an H-plane waveguide housing, particularly suited for duplexing in high-power microwave radar systems.

Design Considerations

The design of the high-power ferrite circulator involved two basic design considerations—the choice of the material and the physical configuration of the junction. Green [1], Stern [2], and Rodrigue [3] have shown that for high-peak-power operation, the ratio $4\pi M_s/\omega$ (where $4\pi M_s$ is the ferrite magnetization parameter and ω is the operating frequency) is one of the factors that determines the peak-power threshold of the device and should be as low as possible, while optimum bandwidth requires a $4\pi M_s$ value in the 800–1200-G range. Consequently, a compromise has to be made. To further improve the peak-power handling of the ferrite, rare earth substitutions for yttrium may be used.

The high average power imposes another requirement on the materials, namely, that the magnetization of the ferrite be stable with temperature. Three appropriate garnets were used during this investigation, namely, two gadolinium and aluminum substituted YIG materials (Trans-Tech G-1006 and G-500), and also G-500 with 4-mole percent of dysprosium (Dy) substituted to enhance the peak-power threshold level of the device. Initial development work was accomplished using the G-1006 material ($4\pi M_s = 400$ G), but it was found that the $4\pi M_s$ of this material was so low as to prevent acceptable operation over the desired 400-MHz frequency range at S band. The next choice of material, G-500 ($4\pi M_s = 550$ G), provided the desired bandwidth while still exhibiting the desirable relatively low $4\pi M_s$ value. The use of the G-500 material with 4 mole percent of Dy for the final model was based on its bandwidth characteristics together with its high-power capability.

A full-height ferrite rod with a thin center metallic pin was the type of center junction utilized as the basic physical design approach for the center junction. One such structure is shown in Fig. 1. This configuration was utilized in order to avoid the problems experienced in high-power microwave ferrite devices. A full-height ferrite rod was first fabricated having an axial hole for center pin placement. The ends of the ferrite rod plus the inside surface of the hole were then electroless plated with copper to a thickness of approximately 0.001 in. This plating served three purposes. First, a good metallic bond to the ferrite insured optimum heat transfer from the ends of the ferrite to the RG-48/U waveguide housing and, also, additional heat transfer to the copper pin, which would be positioned in the ferrite rod. Second, the metallization eliminates any possible air voids which would tend to otherwise cause arcing or breakdown during high-power testing. Third, the metallization eliminates air gaps between the ferrite rod ends and the housing, which typically cause lossy moding spikes in the low-loss transmission direction. A silver conductive paste is used to fill any air gaps between the plated ferrite rod, center pin, and the waveguide housing. Incorporating the thin full-height pin in the ferrite rod has been shown to produce significantly broader operating bandwidths when using full-height ferrite junction designs in addition to the heat-sink effect of the conducting pin. Fixed circulators have been constructed in this configuration which generated greater than 30-percent bandwidth in X band [4]. These X-band circulators were designed through a theoretical analysis, which consisted of solving on a high-speed computer the special case of the central conducting pin, concentric ferrite rod, and external dielectric matching sleeve. This theoretical analysis utilized junction symmetry in the boundary-value problem in order to determine the scattering matrix for the circulator. This theoretical work was extended to S band by Davis and Castillo [5]. Thus the computer program was utilized in order to determine the physical and electrical parameters of the junction region required to yield the desired operating bandwidth, while working with a relatively low ferrite $4\pi M_s$ value. The results of a computer run in S band provided a reasonable and time-saving starting point from which to further optimize this particular type of junction circulator design.

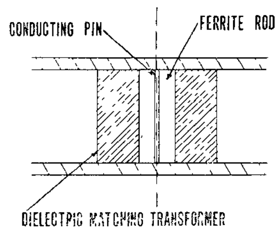

Fig. 1. Basic junction configuration.

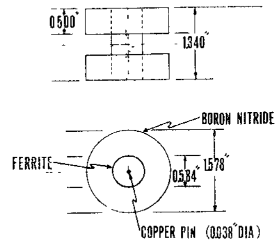

Fig. 2. Circulator junction configuration.

It was found theoretically and verified experimentally that a dielectric matching transformer of relative dielectric constant $\epsilon \approx 2$ produced the best impedance match into the ferrite-loaded junction. A Teflon transformer ($\epsilon \approx 2$) was first utilized, but high-power performance proved to be very poor due to the heat buildup in the ferrite, which was aggravated by the low thermal conductivity of the Teflon. Boron nitride transformers were then investigated since their thermal conductivity is significantly better than both Teflon and the ferrite. The relative dielectric constant of boron nitride is approximately equal to 4; thus the full-height transformer sleeve has to be replaced by two boron nitride rings, resulting in a partial-height transformer yielding a relative $\epsilon \approx 2$. This junction configuration is illustrated in Fig. 2. The low-power performance of the transformer proved to be virtually identical to that of the full-height Teflon sleeve. The benefit gained through the use of boron nitride was indicated by the substantially better heat-sink properties exemplified by the improvement in the device high-power microwave characteristics.

The basic design was then tested using various ferrite materials. Trans-Tech G-1006 was first eliminated at low-power levels due to bandwidth deficiency. G-500 was then tested and found to have excellent bandwidth and operating characteristics at low power, as did G-500 with 4 mole percent Dy substitution. Both of these G-500 materials were then tested at high-power levels, and the respective loss characteristics are indicated in Fig. 3. It is noted that the G-500 material without rare earth substitution quickly enters into nonlinear operation, as shown by the increase in insertion loss to over 1 dB before the peak power reaches 50 kW. The Dy-substituted G-500, on the other hand, yields an increase in the nonlinear threshold due to the substitution of rare earth ions. The result of this substitution is indicated by the lower insertion loss as shown in Fig. 3.

Operating Characteristics

The low-power operating results obtained with the finalized junction design are shown in Fig. 4. The isolation at a particular port was maximized over the desired bandwidth by positioning a capacitive tuning button in the adjacent low-loss port. This was done for each of the successive isolated ports. It is observed that over the frequency range of 3.1–3.5 GHz, the isolation is greater than 22 dB and the insertion loss less than 0.4 dB. A 650-MHz bandwidth is indicated with isolation of at least 20 dB and insertion loss of 0.5 dB maximum. These measurements were made at low-power levels.

High-power measurements were made at the only available high-power source frequency of 3.462 GHz. The high-power results indicated isolation of 20.5 dB and insertion loss of 0.85 dB with input VSWR < 1.25:1. Although this high-power measurement does not guarantee identical operating characteristics over the entire bandwidth, it is expected that this is a nominal representation. By incorporating external cooling fins to the top and bottom of the junction

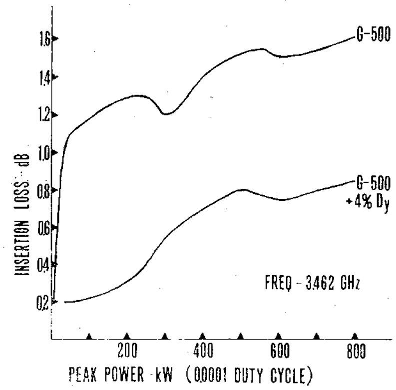

Fig. 3. Insertion loss versus peak power for various ferrites.

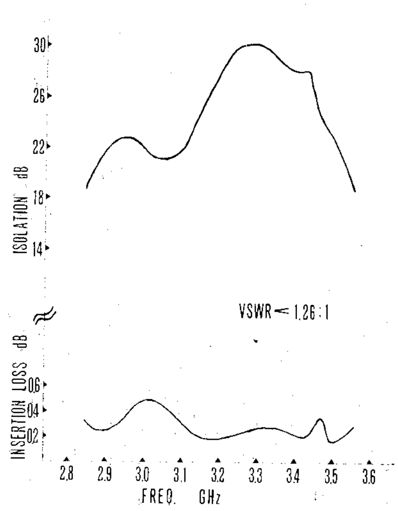

Fig. 4. Circulator operating characteristics.

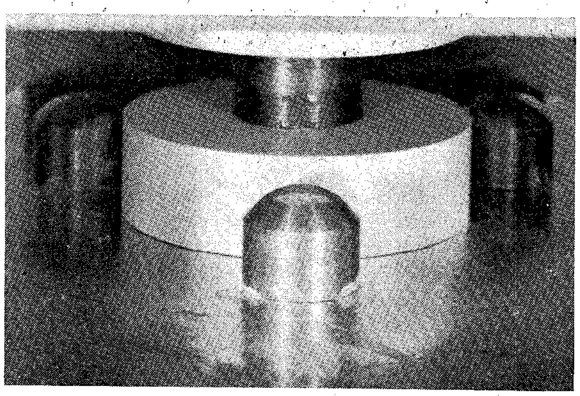

Fig. 5. Internal view of circulator.

housing, the overall microwave high-power operating characteristics could be further improved by this more efficient removal of heat from the junction region. Fig. 5 is a view of a portion of the junction region showing ferrite, boron nitride matching transformer, and capacitive tuning buttons. Fig. 6 is an overall view of the circulator.

Conclusion

The successful design of this high-power S-band circulator clearly demonstrates that, in many cases, a large heavy-differential phase-shift circulator or narrow-band junction circulator can be replaced by this H-plane Y-junction circulator. This unit is substantially smaller in size and weight than a differential phase-shift-type device, and also spans a broader bandwidth than state of the art junction circulators available at these frequencies and power levels. By incorporating cooling fins in the junction housing, one could operate this

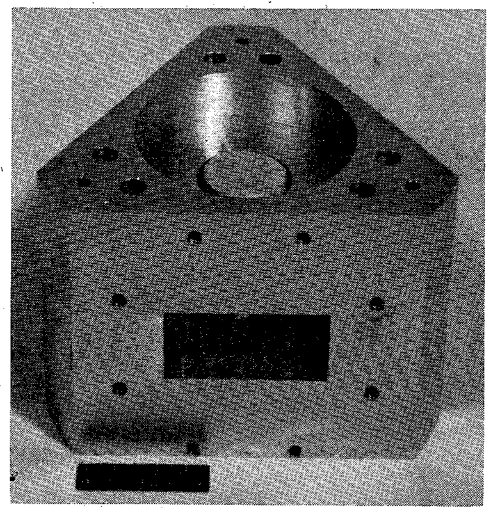

Fig. 6. Circulator configuration.

device at power levels up to 1-MW peak, and 1-kW average, without significantly affecting the operating characteristics of the circulator.

Acknowledgment

The author wishes to thank J. Agrios for adapting and programming the computer analysis which was initially used to design the model, J. LoCicero for his invaluable assistance in fabricating the experimental models constructed during the course of this investigation, and C. Heinzman for his valuable assistance in the area of high-power testing.

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The Digital Twin-Ferrite-Toroid Circular Waveguide Phaser

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***Abstract*—A new microwave structure is proposed, consisting of a circular waveguide loaded with two ferrite toroids circumferentially magnetized at remanence in opposite direction. It is shown that nonreciprocal parameters such as differential phase shift can be doubled with respect to the single toroid configuration. A method for biasing the toroids at remanence in opposite directions by means of a single wire passing through the axis of the waveguide is proposed.**

Modal purity is taken into account in order to select dielectric loading parameters which ensure operation within the modal inversion window in which the TE_{01} mode is dominant. The propagation factor and differential phase shift are computed under these conditions, and their variation with several parameters such as remanent magnetization, toroid location, and toroid thickness is shown.

Introduction

There are at present no exact solutions for the geometries used in several ferrite devices primarily because the exact form of the device entails solving an extremely complex field theoretic problem, while

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