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 together with boron nitride matching transformers.

Introduction

This report describes the development of an air-cooled high power S-band Y junction circulator. This device was developed for a particular S-band radar system where size, weight, bandwidth, and loss characteristics were of paramount importance. Presently available high power S-band circulators (H-plane, E-plane, and differential phase shift units) could meet some of the specific system requirements, but each had at least one area of deficiency. The H-plane circulator discussed in this report meets these requirements with no major deficiency. The design is reasonably compact and lightweight. The unit has no need for cumbersome liquid cooling, and the bandwidth is relatively broad. 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. In our discussions, we define ferrite to include garnets. Green,[1] Stern,[2] and Rodrique[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 of great importance, since it is one of the factors that determines the peak power threshold of the device and should be as low as possible. The bandwidth of the device, however, is also dependent on the $4\pi M_s$ of the ferrite. Optimum bandwidth requires a $4\pi M_s$ value in the 800 to 1200 gauss range while high peak power operation requires a substantially lower value. 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 four mole percent of dysprosium 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 four 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 Figure 1. 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% 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 work was extended to S-band by L. E. Davis and J. B. 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.

Circulator Design

The configuration discussed above 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 .001". 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. Thirdly, 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 tight fitting copper pin is then placed in the ferrite, together with a silver paste, in order to achieve maximum filling of the hole in the ferrite. This conductive paste is also used to fill any air gaps between the plated ferrite rod and the waveguide housing.

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 its thermal conductivity is significantly better than both teflon and the ferrite. The relative dielectric constant of boron nitride is ≈ 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 Figure 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 % Dy substitution. Both of these G-500 materials were then tested at high power levels and the respective loss characteristics are indicated in Figure 3. It is noted that the G-500 material, without rare earch substitution, quickly enters into non-linear operation as shown by the increase in insertion loss over 1 dB before the peak power reaches 50 kW. The Dy substituted G-500, on the other hand, remains at a low level of insertion loss as peak power is increased.

The inherent air gap between the ferrite rod and the boron nitride rings initially caused a breakdown problem during high power measurements. A perfect fit was impossible with these materials so that an adhesive type sealant (Dow Corning 3144 RTV) was used to fill in these circumferential voids and thereby prevent breakdown. The use of this sealant solved the breakdown problem without adding any measurable insertion loss to the device operation.

Operating Characteristics

The low power operating results obtained with the finalized junction design are shown in Figure 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 to 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 is a nominal representation. By incorporating external cooling fins to the top and bottom of the junction housing, the overall microwave high power operating characteristics could be further improved by this more efficient removal of heat from the junction region. Figure 5 is a view of a portion of the junction region showing ferrite, boron nitride matching transformer, and capacitive tuning buttons. Figure 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 device at power levels up to 1 MW peak and 1 KW average without significantly affecting the operating characteristics of the circulator.

Acknowledgement

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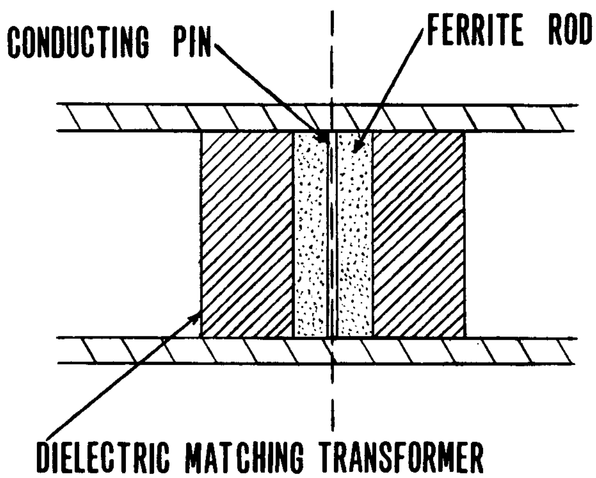

FIG 1 BASIC JUNCTION CONFIGURATION

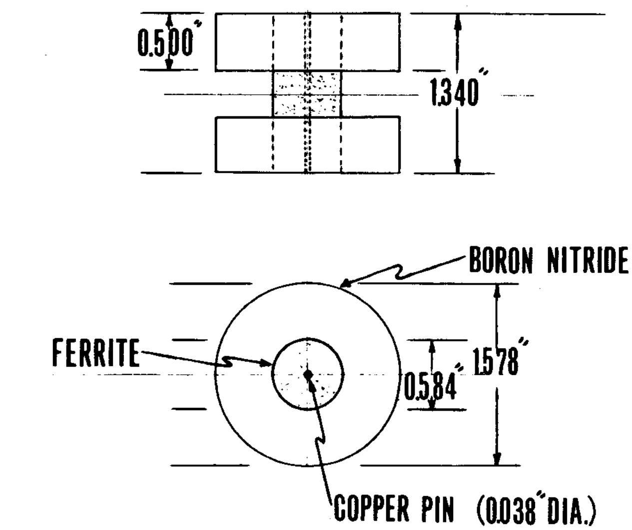

FIG 2 CIRCULATOR JUNCTION CONFIGURATION

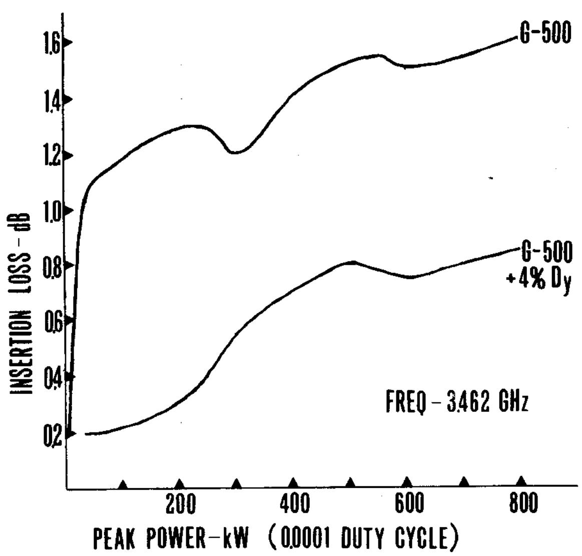

FIG 3 INSERTION LOSS VS. PEAK POWER FOR VARIOUS FERRITES

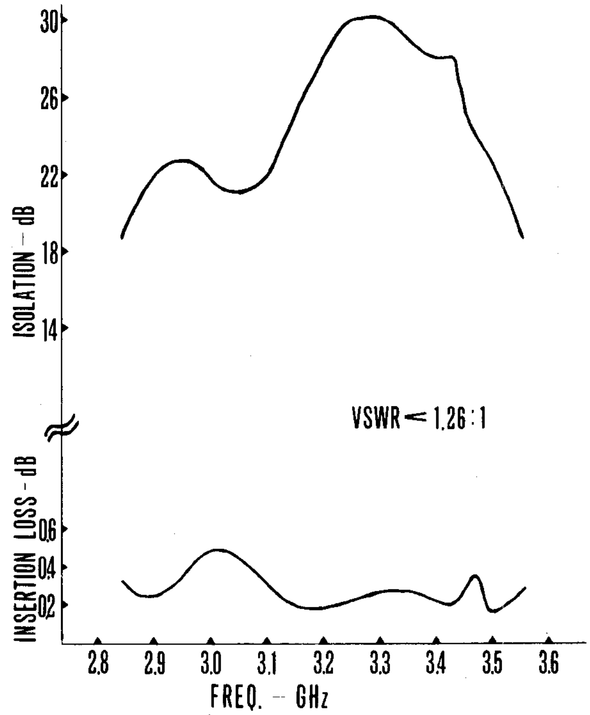

FIG 4 CIRCULATOR OPERATING CHARACTERISTICS

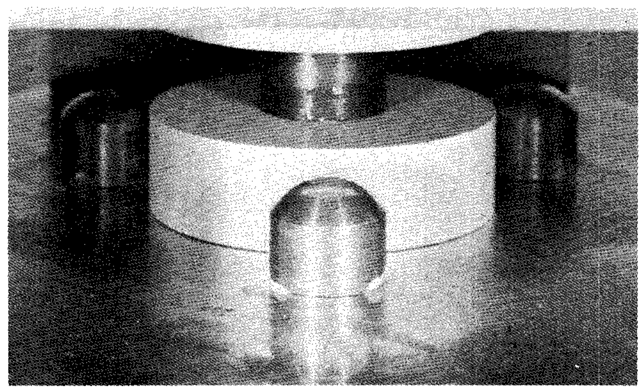

FIG 5 INTERNAL VIEW OF CIRCULATOR

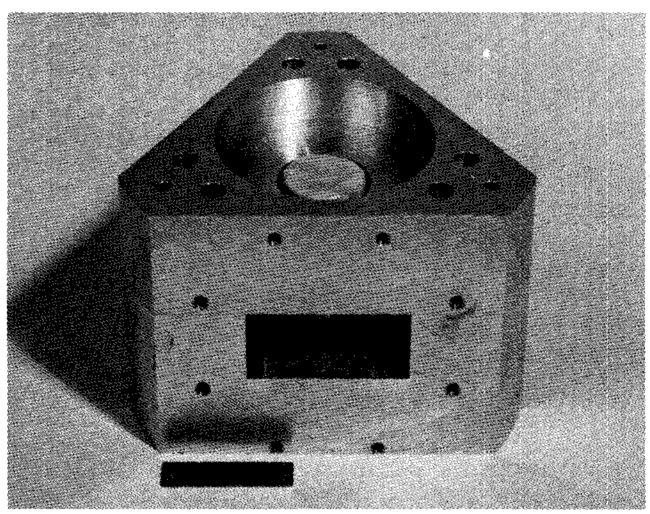

FIG 6 CIRCULATOR CONFIGURATION