X-5. THEORETICAL DESIGN OF STATIC AND LATCHING FERRITE 3-PORT AND 4-PORT SYMMETRICAL WAVEGUIDE CIRCULATORS

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Objectives and Background. Compact 3-port microwave ferrite circulators have become widely used since 1960, but they have generally been empirically designed and their operation is not well understood. The success of the experimental approach has resulted in less emphasis on the theoretical explanation of these devices, and this situation is now retarding the development of the more complicated 4-port circulators. However, extending the work of Auld and Davies, IBM 7040 computer programs have recently been written in this department that predict and display the swept-frequency performance of 3-port and 4-port waveguide circulators. There are several objectives in this work: (1) to extend these computer programs, and the associated theory, to predict the performance of static and latching ferrite circulators in order that the performance of various ferrite configurations can be assessed and compared before they are built; (2) to optimize the many variables to obtain broadband performance where possible; (3) to build some devices to check the theory; (4) to use the theory to gain some insight into the physical behavior of symmetrical waveguide circulators; (5) to investigate phase shift in these devices.

In 1959 Auld[1] considered the synthesis of symmetrical waveguide junction circulators using the scattering matrix. In 1962, Davies[2] carried out an analysis of the fields in an m-port H-plane waveguide junction centrally loaded with ferrite, which enabled the eigenvalues of the scattering matrix to be expressed in terms of the ferrite parameters. In 1964 Davis, Coleman and Cotter[3] described the results of an experimental investigation of 4-port circulators with two ferrite configurations. In the light of these results, Davies[4] modified his theory to incorporate one of these two configurations and Longley and Parsonson[5] have used the modified theory to obtain computed predictions of very broadband (40%) 3-port waveguide circulators. The configuration considered in these latter devices consisted of a cylindrical ferrite post, extending between the broad walls of the waveguide, surrounded by a dielectric sleeve, with a very thin conducting pin (approximately 0.010 inch in diameter) down the center of the ferrite. Their experimental test devices had very encouraging performance even though they had bandwidths smaller than the predicted values.

Ferrite Configurations and Computations. Since 4-port circulators have advantages over 3-port circulators as real-time delay lines in pulsed phased arrays, the theoretical approach of Davies[2] has been modified and IBM 7040 computer programs have been written for both 4-port and 3-port devices. The scattering matrix of a particular configuration is computed every 100 MHz over the X-band waveguide range, 8 - 12 GHz, but the results can be scaled to any other frequency range. The printed output is in the form of a swept-frequency display of circulator performance, for a constant value of polarizing magnetic field. That is, the output from each port of the proposed circulator is plotted in terms of power loss over the waveguide bandwidth. A dissipation-free system is assumed, and therefore, the predicted losses are entirely due to scattering. Ferrite/dielectric structures have been selected that are amenable to theoretical analysis and are suitable for latching operations, and programs have been written to predict the performance of the following configurations in 3-port and 4-port waveguide junctions:

(a) ferrite rod with one or two dielectric sleeves
(b) ferrite rod with a central metal pin, with or without a dielectric sleeve
(c) ferrite tube with a dielectric filling and a dielectric sleeve.

Thus, in each program all or most of the following are available as variables: number of ports (m); internal static magnetic field (H_o); ferrite saturation magnetization ($4\pi M_s$), linewidth (ΔH) and ferrite dielectric constant (ϵ_r); ferrite rod radius (R); metal pin radius (RP); if tubular ferrite, tube inside radius (RP) and dielectric constant of dielectric filling (ϵ_{ro}); for the first dielectric sleeve the outer radius (R_1) and dielectric constant (ϵ_{r1}); for the second dielectric sleeve, the outer radius (R_2) and dielectric constant (ϵ_{r2}). The values of these variables can be seen printed along the top line of each computed swept-frequency display. Any value of magnetic field may be selected but we have restricted the range to approximately 20 increments of 50 oersteds, or until the effective permeability is reduced to zero, whichever is the sooner. The frequency range in the current work is 8 - 12 GHz and X-band waveguide is used (a = 0.900 in.) but the computations can be carried out with other values or the results scaled.

Four preliminary results are shown in Figures 1 - 4. These simulated swept-frequency displays show two 3-port circulators and two 4-port circulators, all four devices using commercially available ferrites or garnets. Fig. 1 predicts that the configuration in a 3-port junction will provide isolation $\geq$ 20 dB from 8 - 12 GHz. This configuration is very similar to that reported by Longley and Parsonson[5]. Varying the radius of the metal pin affects the performance as follows: decreasing to 0.005 cm lowers the frequency and results in isolation $\geq$ 15 dB from 8 - 10.5 GHz; increasing the pin radius to 0.025 cm, increases the frequency and results in isolation $\geq$ 15 dB from 9.5 - 12 GHz. Fig. 2 predicts that a broadband 3-port circulator can be fabricated from a hollow ferrite tube. This is a novel configuration which appears promising and may have cooling advantages in high-power applications if the performance can be improved. Figs. 3 and 4 show 4-port circulators. In these characteristics the sharpness of the isolation curve is noteworthy compared to the broader bandwidth insertion loss, reflection loss and cross-decoupling curves. This feature is the heart of the problem of 4-port circulator design. The latter three characteristics of a 4-port circulator are interdependent and can be affected by external matching. But it can be shown that the isolation at the fourth port is largely unaffected by external tuning (except by magnetic field) and consequently is governed principally by the ferrite configuration itself. Thus, 4-port circulator design is fundamentally a problem of finding a configuration that will give the desired isolation characteristic, and then matching it. The computer programs enable a fast search to be made for these improvements. Preliminary experimental testing of these devices is in hand.

The main assumptions in the analysis are: (a) that the ferrite is saturated and uniformly magnetized; (b) that the devices are lossless; and (c) that in the absence of experimental values of the susceptibility tensor components over this wide frequency range, theoretical values may be calculated from the Polder-Hogan equations. It is well known that these equations are quantitatively inaccurate, but if the effects of various material parameters ($4\pi M_s$, ΔH, ε_r), the wide frequency range, and facility to adjust the applied field are to be estimated, it is necessary to use these equations; (d) that there is no rf field variation in the direction of the applied magnetic field. If this is not assumed, the modes are not separable and the problem is considerably complicated.

To summarize, it is believed that a theoretical approach as outlined, offers a means whereby many configurations can easily and rapidly be assessed before manufacture, and only those with promising performance need be built and finally experimentally adjusted. Thus, many hours of testing useless configurations may be avoided. Also, it may ultimately give some insight into the limitations in the performance of these devices.

References.

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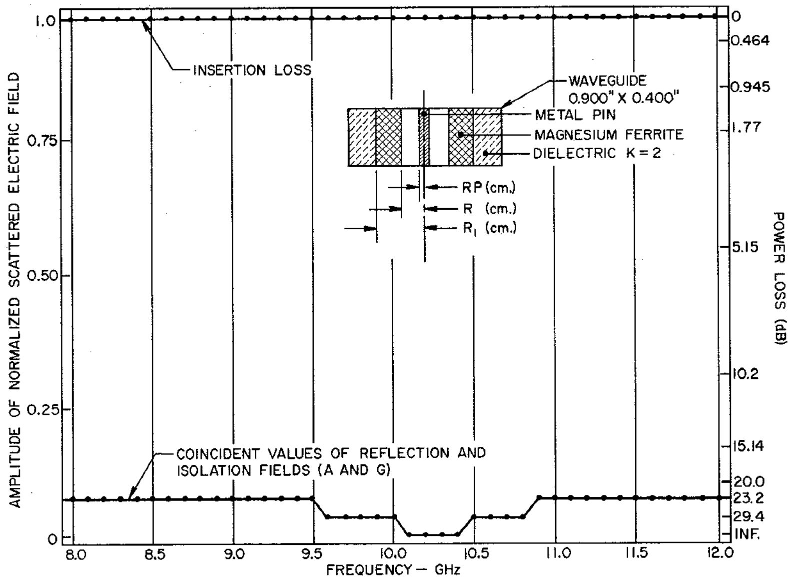

Figure 1. Predicted Performance of a 3-Port Circulator with a Central Metal Pin, Ferrite Post and One Dielectric Sleeve

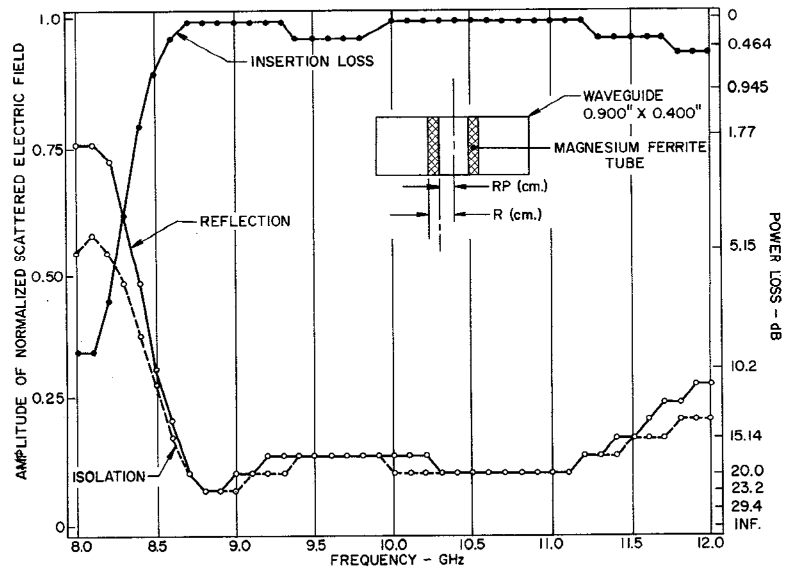

Figure 2. Predicted Performance of a 3-Port Near-Circulator With a Hollow Ferrite Tube

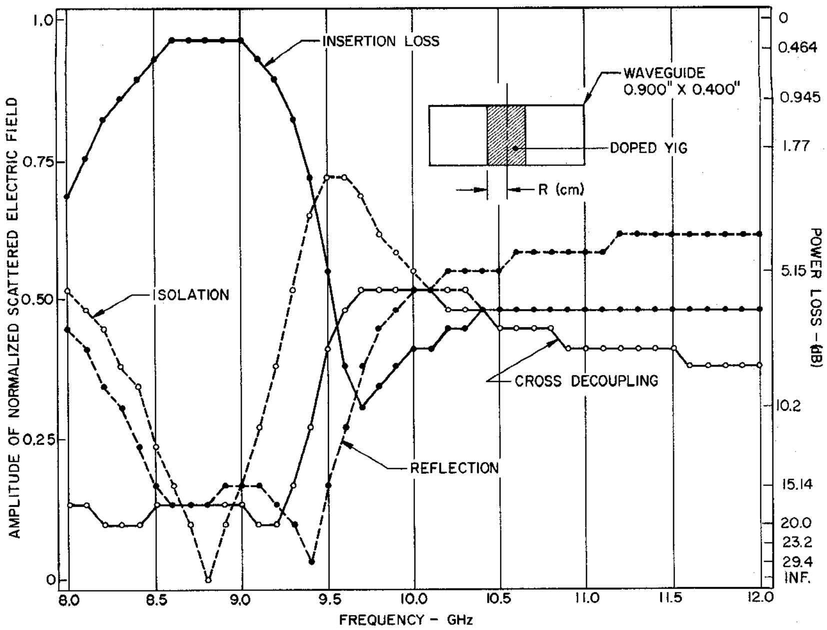

Figure 3. Predicted Performance of a 4-Port Circulator with a Garnet Post

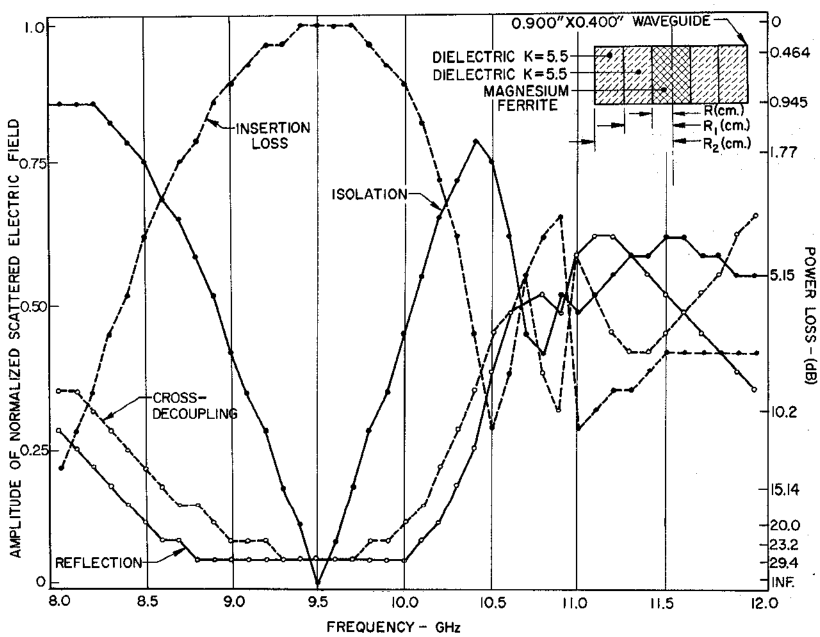

Figure 4. Predicted Performance of 4-Port Circulator with 2 Dielectric Sleeves