Short Papers

Losses in Multiport Stripline/Microstrip Circulators

Hoton How, Carmine Vittoria, and Ronald Schmidt

***Abstract*— We have included losses in the analysis of a $3N$-port stripline/microstrip circulator and have reformulated the circulation conditions previously postulated for the lossless case. Our calculations have been compared to three published data on circulator designs biased above ferromagnetic resonance (FMR). Scattering parameters at each port have been calculated as a function of assumed material losses and coupling capacitance of a multiport circulator.**

***Index Terms*—Circulator, ferrite junction, magnetic loss, $3N$-port device.**

I. Introduction

The first commercial microwave circulator appeared in the early 1950's, while a full theoretical account of its operation was not published until 1962 [1]. Fay and Comstock presented a working model for a Y-junction circulator based on the splitting of the two counter-rotating magnetic dipole modes of the ferrite in the presence of a magnetic biasing field [2]. Thus, the present theory is able to calculate reasonably well the required external magnetic field and operating frequency at which the circulation condition is obeyed. However, present theory is not able to predict insertion loss or the coupling efficiency between ports at circulation. Clearly, the insertion loss must somehow be related to the intrinsic losses of the ferrite—both magnetic and electric losses. In this paper, we want to elevate this qualitative notion to a more precise quantitative prediction of insertion loss at circulation based upon intrinsic loss of the ferrite and external microwave loading to the circulator.

We have avoided the traditional approach which relies on the use of Bessel functions, which take only real numbers as arguments since in the previous calculations, intrinsic losses are assumed to be zero. Instead, a new computational algorithm have been developed which directly processes complex numbers upon which the circulator's interport impedance can be conveniently calculated.

Also, previous theoretical formulations of circulator performance was based upon the principle that, at the circulation condition, the transmission efficiency between the two circulation ports was 100% and the isolation port was zero. This principle cannot be applied here. We need to relax this principle by allowing the circulation transmission to be a maximum, since there may be dissipation included in the ferrite. This suggests a theoretical formalism in which some type of mathematical extremum conditions are derived from the equation of motion of the magnetization.

Manuscript received April 10, 1995; revised February 13, 1998. This work was supported by the National Science Foundation under Contract DMI-9461670.

H. How is with ElectroMagnetic Applications, Inc., Boston, MA 02109 USA.

C. Vittoria is with the Electrical and Computer Engineering Department, Northeastern University, Boston, MA 02115 USA.

R. Schmidt is with the Microelectronics Products Division, Radar Products Operations, M/A-COM. Inc., Burlington, MA 01803 USA.

Publisher Item Identifier S 0018-9480(98)03160-3.

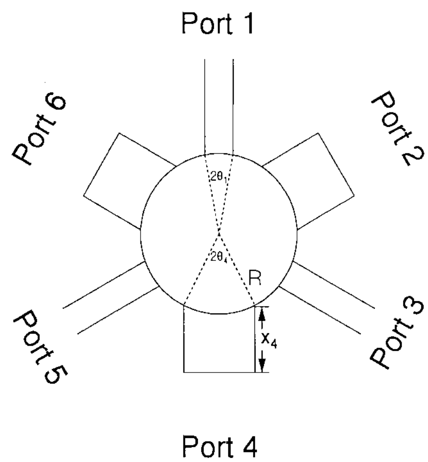

Fig. 1. Schematic drawing of a six-port circulator.

II. Formulation

For a circulator junction (besides conventional three through-ports), additional ports may be included which act as tuning stubs whose lengths need to be considered separately for each case to account for the resultant coupling admittance to the central ferrite junction. Fig. 1 depicts the geometry of a six-port junction circulator in which ports 1, 3, and 5 are through ports which are connected to matched loads. The height of the ferrite disk(s) will affect the input impedance of the junction at circulation, which needs to be explicitly considered to design a matched load (50 Ω). Ports 2, 4, and 6 are open-circuited ports, which behave similarly to tuning stubs in transmission lines, providing additional control over the performance of the circulator. In order to achieve cyclic operation of a circulator, threefold symmetry must be retained in the junction geometry.

In this paper, the operation of a general $3N$-port circulator is formulated. The $3N$ ports are numbered from $1N$–$3N$ with the through ports denoted as 1, $1 + N$, and $1 + 2N$. The threefold symmetry of the junction requires ports m, $m + N$, and $m + 2N$ to be characterized by the same parameters. Here, m is an integer and $1 \leq m \leq N$. The azimuthal angle at the center of port α is denoted as ϕ_α and $\phi_\alpha = 2\pi(\alpha - 1)/3N$ for $1 \leq \alpha \leq 3N$. The port suspension angle and the effective loading impedance at port α are denoted as $2\theta_\alpha$ and Z_α, respectively. Port 1 will be used as the input port, and ports $1 + N$ and $1 + 2N$ are either the transmission port or the isolation port, respectively.

The ferrite disk is of radius R and height h, whose dielectric constant, dielectric loss tangent, saturation magnetization, and ferromagnetic resonance (FMR) linewidth are denoted as ϵ_f, $\tan\delta$, $4\pi M_s$, and ΔH, respectively. The ferrite disk is surrounded by a dielectric matching material, filling the space between the metal strip and the ground plane(s), making up for the stripline/microstrip feeder lines. The dielectric constant of the dielectric filling material is denoted as ϵ_d. The RF–electromagnetic fields excited within the ferrite disk(s) responsible for circulation operation are TE waves possessing no variations along the dc-field direction, the axial direction of the disk denoted as the z-axis. The permeability of the ferrite is described by a Polder tensor in the following form:

$$\underline{\boldsymbol{\mu}} = \begin{pmatrix} \mu & i\kappa & 0 \\ -i\kappa & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

where μ and κ are given as

$$\mu = 1 + \frac{f_o f_m}{f_o^2 - f^2} \quad \kappa = \frac{f f_m}{f_o^2 - f^2} \tag{2}$$

and f is the frequency, and f_m and f_o are defined as

$$f_m = 4\pi\gamma M_s \quad f_o = \gamma H_i.$$

Here, γ is the gyromagnetic ratio ($\gamma = 2800$ Oe/GHz) and H_i denotes the internal dc field within the ferrite. The time dependence of $\exp(-i\omega t)$ has been assumed in (1) and (2).

From [3], the scattering matrix of the circulator junction is

$$\underline{\underline{\mathbf{S}}} = \underline{\underline{\mathbf{I}}} - (2/Z_d)(\underline{\underline{\mathbf{Z}}} + \underline{\underline{\mathbf{G}}})^{-1} \tag{3}$$

where $\underline{\underline{\mathbf{I}}}$ denotes the unit matrix, $\underline{\underline{\mathbf{G}}}$ is the matrix of interport impedance given by

$$G_{\alpha\beta} = -iZ_f\left(\frac{\theta_\beta}{\pi}\right) \sum_{n=-\infty}^{\infty} \left[\frac{n}{x}\left(1 - \frac{\kappa}{\mu}\right) - \frac{J_{n+1}(x)}{J_n(x)}\right]^{-1} \cdot \left(\frac{\sin n\theta_\alpha}{n\theta_\alpha}\right)\left(\frac{\sin n\theta_\beta}{n\theta_\beta}\right) e^{in(\phi_\alpha - \phi_\beta)} \tag{4}$$

and $\underline{\underline{\mathbf{Z}}}$ is the impedance of the ports defined as

$$Z_{\alpha\beta} = i\delta_{\alpha\beta} Z_d \cot(x_\alpha \omega \sqrt{\epsilon_{\rm re}}/c). \tag{5}$$

Here, x_α is the length of port α, and $\epsilon_{\rm re}$ denotes its effective relative dielectric constant. For stripline ports, $\epsilon_{\rm re} = \epsilon_d$, and for microstrip ports, $\epsilon_{\rm re} = 1 + q(\epsilon_d - 1)$, where q denotes the filling factor of the dielectric in the microstrip transmission lines. In (4), variable x is defined as

$$x = kR$$

k is the wave propagation constant given by

$$k = \omega(\mu_{\rm eff}\epsilon_f)^{1/2}/c$$

$\omega = 2\pi f$ is the angular frequency, and $\mu_{\rm eff}$ is the effective permeability of the ferrite given by

$$\mu_{\rm eff} = (\mu^2 - \kappa^2)/\mu.$$

The effective wave impedances in the ferrite and dielectric filling materials are, respectively,

$$Z_f = (\mu_{\rm eff}\mu_o/\epsilon_f\epsilon_o)^{1/2}$$

and

$$Z_d = (\mu_o/\epsilon_d\epsilon_o)^{1/2}.$$

In (4), we have to evaluate Bessel functions with complex arguments if dielectric and magnetic losses are included in the formulation; i.e., dielectric constant of the ferrite ϵ_f needs to be replaced by $\epsilon_f(1 + i\tan\delta)$, where $\tan\delta$ denotes the dielectric loss tangent. Magnetic loss can be accounted for if the internal field H_i is modified to $H_i - (i\Delta H/2)/(f/f_r)$, where f_r denotes the frequency at which the linewidth ΔH was measured (usually at 10 GHz). Therefore, when complex ϵ_f and H_i are used, Z_f, k, and $\mu_{\rm eff}$ become all complex numbers, which result in a complex argument for Bessel functions $x = kR$. We have purposely arranged Bessel functions in (4) as ratios involving successive orders. As such, we may use the following algorithm to evaluate these ratios [4]:

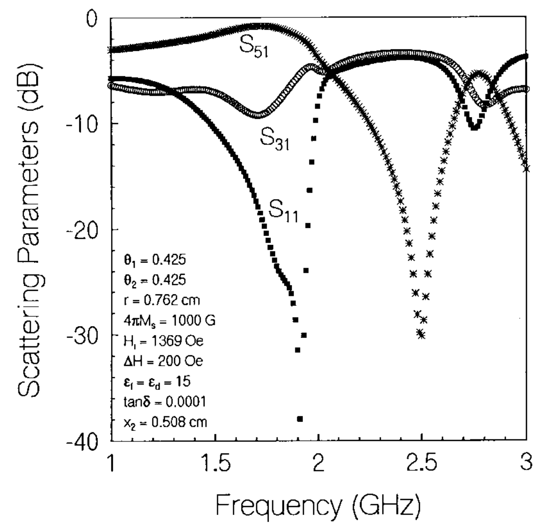

Fig. 2. Calculated scattering parameters for Riblet's six-port circulator design.

$$\frac{J_\nu(z)}{J_{\nu-1}(z)} = \frac{1}{(2\nu+1)z^{-1}} - \frac{1}{2(\nu+1)z^{-1}} - \frac{1}{2(\nu+2)z^{-1}} - \cdots \tag{6}$$

where z can be a complex number and ν a real number (not necessarily an integer). Equation (6) is in the form of continued fractions, which converges very rapidly, and the radii of convergence in the z and the ν variables are both infinite. For positive integer n no larger than 20, and for a real positive x smaller than 100, the above expression, which evaluates $J_n(x)/J_{n+1}(x)$ to an accuracy within 10^{-15}, requires less than 25 terms. For larger n, more terms are needed, and for $n = 100$, about 45 terms are required to achieve an accuracy of 10^{-15}.

In a lossless junction, the circulation condition is $S_{11} = 0$. However, in the presence of losses, circulation conditions are modified as follows:

$$|S_{11}| = \text{minimum} \quad |S_{(1+N)1}| = \text{maximum (minimum)}. \tag{7}$$

These circulation conditions imply $|S_{(1+2N)1}|$ to be a minimum (maximum) if threefold symmetry is retained in the junction geometry. That is, as the $(N+1)$th port is optimized to be the transmission (isolation) port, the $(2N+1)$th port will be (automatically) the isolation (transmission) port. Therefore, search of circulation conditions requires optimization of scattering parameters S_{11} and $S_{(1+N)1}$, with respect to the parameters of the junction. In the following calculations, we will use ϵ_d, R, and H_i as the three independent variables exploiting the so-called multidimensional simplex method in optimizing the circulation conditions (7). The multidimensional simplex method [5], although it is relatively slow in comparison with other slope-related methods, is quite robust and efficient in the present calculations. For most calculations, no more than 300 iterations are required to yield convergence in an accuracy of 10^{-5}.

III. Calculation Results

Fig. 2 shows the calculated scattering parameters as a function of frequency for a six-port stripline circulator operating above FMR

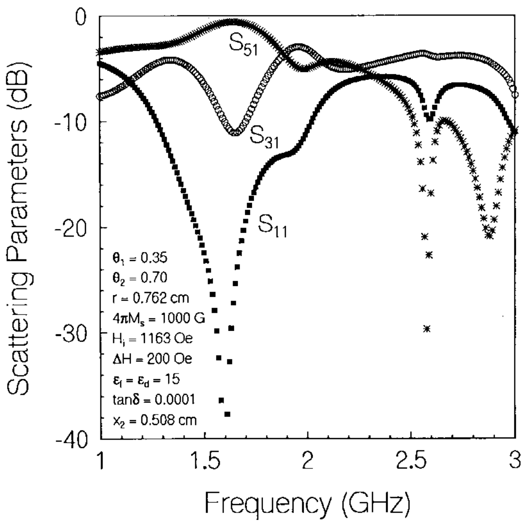

Fig. 3. Optimization of Riblet's six-port circulator design subject to one circulation condition.

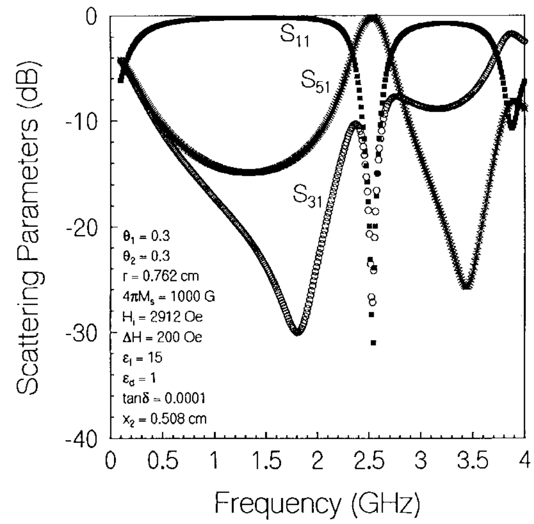

Fig. 4. Optimization of Riblet's six-port circulator design subject to two circulation conditions.

resonance. This design, which was originally proposed by Riblet, was intended for high-power wide-band operation [6]. For this design, the same ferrite is used as the dielectric filling material and the secondary (tuning) ports possess the same suspension angle as the primary (through) ports. The circulator parameters used by Riblet are as follows: $r = 0.762$ cm, $4\pi M_s = 1000$ G, $\epsilon_f = \epsilon_d = 15$, $\theta_1 = \theta_2 = 0.425$, and $x_1 = 0.508$ cm [6]. The external field used by Riblet was 2000 Oe [6]. To minimize the return loss, we have found that the ferrite junction shall be biased at an internal field of intensity 1369 Oe. The loss parameters used in the calculations are $\Delta H = 200$ Oe and $\tan\delta = 10^{-4}$. It is seen in Fig. 2 that the insertion loss occurs with a minimum of -0.797 dB at 1.72 GHz. The transmission band may be defined, at which the return loss is larger than 15 dB. As such, the transmission band extends from 1.66 to 1.96 GHz. Thus the bandwidth is approximately 17.2% of the transmission frequency. Indeed, it is a wide-band circulator biased above resonance, as claimed by Riblet [6]. However, in [6], no data were reported on scattering parameters and there is no way to compare our calculations with experiments.

In Fig. 3, Riblet's design has been optimized for the return loss using θ_1 and θ_2 (half the suspension angles of the ports) as additional variables. We found that $|S_{11}|$ can be minimized when θ_1 and θ_2 take the following values: $\theta_1 = 35$ and $\theta_2 = 0.70$. The internal field now requires 1163 Oe. In Fig. 3, it is seen that the insertion loss has been reduced to a value of -0.56 dB at 1.64 GHz. The transmission band extends from 1.37 to 1.77 GHz and the bandwidth is approximately 24.4% of the transmission frequency. However, we must say that both designs of Figs. 2 and 3 are not good circulators, since the isolation of these two devices are too low to be practically useful.

As was mentioned before, both $|S_{11}|$ and $|S_{(1+N)1}|$ need to be optimized to provide global, but not local, circulation operation. Fig. 4 shows such a design originated from Riblet's parameters. In this case, θ_1 and θ_2 are both found equal to 0.3 and ϵ_d is equal to 1, which is different from that of the ferrite material. The internal bias field intensity is 2912 Oe. As shown in Fig. 4, the calculated insertion loss minimum is now located at 2.528 GHz with a value of -0.193 dB. The return loss and isolation are all larger than 15 dB with the transmission band extending from 2.451 to 2.696 GHz. The design does not show wide-band operation, since the bandwidth is only approximately 6.1% of the transmission frequency. However, the advantage of using the design of Fig. 4 is that it is easy to be fabricated since air can be conveniently used as the dielectric filling material. When applied at high power, air exhibits the highest dielectric breakdown voltage and, hence, the design can be advantageously adopted. Furthermore, it is seen in Fig. 4 that the transmission band is surrounded by two very wide stopbands at which the circulator becomes highly reflective. The reflection at these two stopbands are roughly approximately -0.3 and -1 dB, respectively. The circulator can thus be deployed in front of a frequency-selective radome which, while it is able to transmit/receive signals at the desirable frequencies near 2.528 GHz, effectively blocks other unwanted jamming signals above and below the transmission band in wide frequency ranges to protect the electronics inside the radome.

IV. Conclusion

Circulation operation in a general $3N$-port stripline/microstrip circulator has been formulated. Losses of various kinds have been included in this paper's analysis and the traditional circulation conditions have been rephrased. Effective numerical algorithms have been reported, which efficiently and accurately evaluate the ratio of Bessel functions of subsequent orders even for complex arguments. In the Riblet's design [6], optimization of the circulation conditions has been explicitly carried out, which results in a practical circulator with very wide stopband protection. This circulator design may have potential for radome applications.

References

[1] H. H. Bosma, "On stripline Y-circulation at UHF," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 61–72, Jan. 1964.

[2] C. E. Fay and R. L. Comstock, "Operation of the ferrite junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 15–21, Jan. 1965.

[3] H. How, T. M. Fang, C. Vittoria, and R. Schmidt, "Design of six-port stripline ferrite junction circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-42, pp. 1272–1275, July 1994.

[4] *Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables* (Na. Bureau Standards, Appl. Math. Series), M. Abramowitz and I. A. Stegun, Eds. Washington, DC: Dept. Commerce, Nat. Bureau Standards, 1964, vol. 55, p. 363.

[5] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes*, New York: Cambridge Univ. Press, 1992, ch. 10.

[6] C. P. Riblet, "Techniques for broad-banding above resonance circulator junctions without the use of external matching network," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 125–129, Feb. 1980.