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Magnetic losses in stripline/microstrip circulators

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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 below and above ferrimagnetic resonance. Scattering parameters at each port have been calculated as a function of assumed material losses and coupling capacitance of a multiport circulator. Wide transmission band or wide stop bands may be possible for a six port circulator biased above ferrimagnetic resonance.

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INTRODUCTION

The present theory is able to calculate reasonably well the required external magnetic field and operating frequency at which the circulation condition of a stripline/microstrip circulator is obeyed. However, the 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, new computational algorithms have been developed which directly process complex numbers upon which the circulator's interport impedances can be conveniently calculated. Also, previous theoretical formulations was based upon the assumption that at the circulation condition the transmission efficiency between the input and the circulation ports was 100% and the isolation port was zero. This assumption 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 sort of mathematical extremum conditions are derived from the equation of motion of the magnetization. We find that our formulation predicts exactly the same circulation conditions as derived by previous papers using the conventional formalism.¹⁻³ Once we were able to predict the circulation conditions calculated by others, we then calculated the insertion loss, isolation efficiency, and circulation transmission efficiency for various cases by including the ferrite losses in the formalism. Calculations compare quite well with measurements.¹⁻³

FORMULATION

In this paper we define a $3N$ -port circulator to be a multi-port ferrite-junction circulator in which three ports are

through ports capable of signal circulation in the normal sense and the other $(3N-3)$ ports are open-circuited ports which are used to provide additional capacitance tuning. 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 at port α is $2\theta_\alpha$. Port 1 will be considered 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 , height h , whose dielectric constant, dielectric loss tangent, saturation magnetization, ferrimagnetic resonance (FMR) linewidth are denoted as ϵ_i , $\tan \delta$, $4\pi M_i$, 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_j .

The six-port circulator has been previously formulated and reported in Ref. 3. We derive in this paper the formulation of a general $3N$ -port circulator in which the ports may not necessarily have the same port angles. Denote a_{in} as the incident rf-magnetic field at port 1 and a_α , $1 \leq \alpha \leq 3N$, as the average rf-magnetic field at port α . Analogous to the derivations in Ref. 3 a_α can be solved in terms of a_{in} from the following $3N$ coupled linear equations:

$$\sum_{\beta=1}^{3N} (Z_\alpha \delta_{\alpha\beta} + G_{\alpha\beta}) a_\beta = 2a_{in} Z_\alpha \delta_{\alpha 1}, \quad \text{for } 1 \leq \alpha \leq 3N, \quad (1)$$

where $G_{\alpha\beta}$ are the interport impedances given by

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

$$x = kR, \quad k = \omega(\mu_{\text{eff}}\epsilon_f)^{1/2}/c,$$

$$Z_d = (\mu_0/\epsilon_d\epsilon_0)^{1/2}, \quad Z_f = (\mu_{\text{eff}}\mu_0/\epsilon_f\epsilon_0)^{1/2},$$

$$\begin{aligned} \mu_{\text{eff}} &= (\mu^2 - \kappa^2) / \mu, \quad \mu = 1 + f_0 f_m (f_0^2 - f^2), \\ \kappa &= f f_m / (f_0^2 - f^2), \\ f_m &= 4\pi\gamma M_s, \quad f_0 = \gamma H_i. \end{aligned} \quad (2)$$

H_i is the internal dc magnetic field, c denotes the speed of light in vacuum, γ the gyromagnetic ratio, and $\delta_{\alpha\beta}$ is the Kronecker delta function. Finally, the wave impedance viewed at port α is

$$Z_\alpha = iZ_d \cot(x_\alpha \omega \sqrt{\epsilon_{rc}} / c).$$

For stripline port $\epsilon_{rc} = \epsilon_d$, and for microstrip port $\epsilon_{rc} = 1 + q(\epsilon_d - 1)$, where q denotes the filling factor of the dielectric in the microstrip transmission line.

We note that Eq. (2) can be evaluated only if $x(=kR)$ is real. However, when material becomes lossy, both dielectric and magnetic imperfections need to be accounted for explicitly. For lossy ferrites the dielectric constant ϵ_f shall be replaced by $\epsilon_f(1 + i \tan \delta)$ and the internal field H_i by $H_i - (i\Delta H/2)f/f_i$, where f_i denotes the frequency at which the linewidth ΔH was measured (usually at 10 GHz). As such, x becomes a complex number and Eq. (2) can no longer be appropriate for numerical evaluation. Other numerical schemes have to be used as an alternative. Actually, Eq. (2) has been purposely cast in the form which facilitates complex-number calculation. That is, the ratio between two Bessel functions of subsequent orders can be expressed in a form involving continued fractions:⁴

$$\frac{J_\nu(z)}{J_{\nu-1}(z)} = \frac{1}{2\nu z^{-1}} - \frac{1}{2(\nu+1)z^{-1}} - \frac{1}{2(\nu+2)z^{-1}} - \dots, \quad (3)$$

in which z can be a complex number and ν a real number (not necessarily an integer). Equation (3) converges rather rapidly and the radii of convergence in the z and the ν variables are both infinite.

The scattering parameters can now be calculated as

$$\begin{aligned} S_{11} &= 1 - a_1/a_{\text{in}}, \quad S_{(1+N)1} = -a_{1+N}/a_{\text{in}}, \\ S_{(1+2N)1} &= -a_{1+2N}/a_{\text{in}}. \end{aligned} \quad (4)$$

The circulation conditions in the presence of material imperfections are rephrased as

$$\begin{aligned} |a_{11}| &= \text{maximum}, \\ |a_{1+N}| &= \text{minimum (or maximum)}, \\ |a_{1+2N}| &= \text{maximum (or minimum)}. \end{aligned} \quad (5)$$

Equation (5) describes the case when port $1+N$ is the transmission (isolation) port and port $1+2N$ is the isolation (transmission) port. We note that Eq. (5) needs to be maximized/minimized for at least two conditions, the third one will hold automatically due to the three-fold symmetry of the ferrite junction. Optimization of scattering parameters, or searching for circulation conditions, Eq. (5), needs to be performed with respect to, at least, two independent circulator variables with others being treated as parameters. Traditionally, ϵ_i and R were used as variables to solve for the "lossless" circulation conditions, $|a_{11}|=1$ and, say,

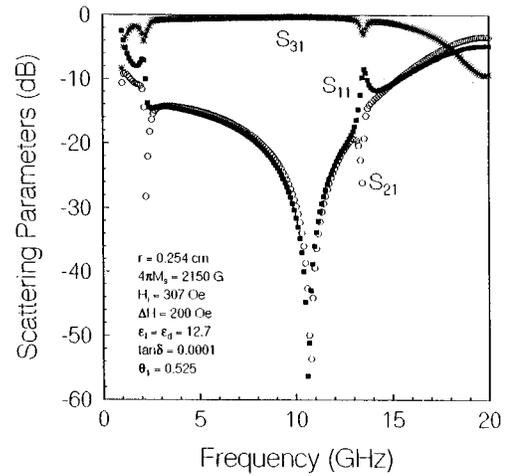


FIG. 1. Optimization of Wu and Rosenbaum's circulator design for better isolation and insertion loss.

$|a_{1+N}|=0$, other parameters are specified beforehand, such as the desired circulation frequency, port suspension angle(s), internal field, and other parameters characterizing the ferrite material. In this paper we may use any of the quantities, f , θ_α , ϵ_i , R , and/or H_i as the independent variables exploiting the so-called multidimensional simplex method in optimizing the circulation conditions, Eq. (5). 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.

RESULTS

Figure 1 shows the calculated scattering parameters of the optimized design of the three-port circulator proposed by Wu and Rosenbaum.¹ In this design the ferrite used was magnesium ferrite (TT1-390, Trans-Tech, MD) possessing the following parameters: $4\pi M_i=2150$ G, $\Delta H=540$ Oe, $\epsilon_f=12.7$ ($=\epsilon_d$), and $\tan \delta=2.5 \times 10^{-4}$. In the calculation we also use $r=0.254$ cm, and $\theta_i=0.525$ rad. After optimization of Eq. (5) with respect to H_i and f , we obtain $H_i=307$ Oe

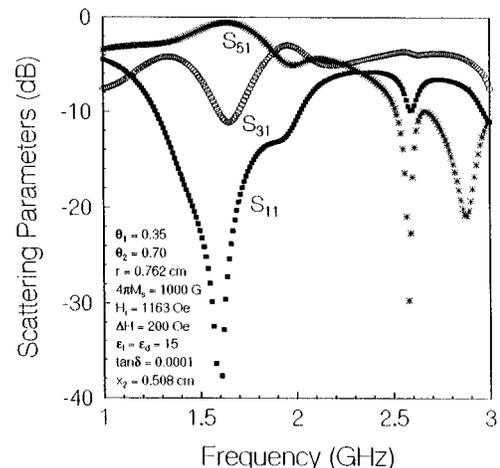


FIG. 2. Optimization of Riblet's sixport circulator design allowing for wide-band transmission operation.

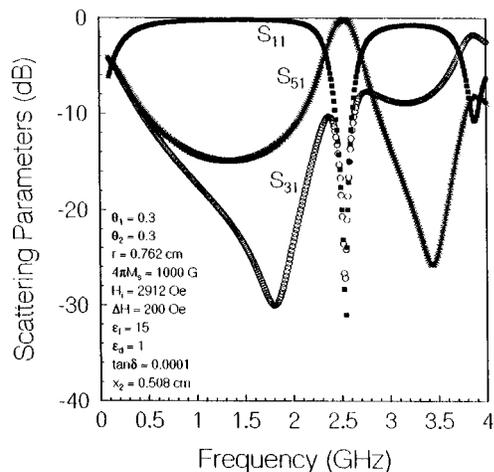


FIG. 3. Optimization of Riblet's sixport circulator design allowing for wide stop band protection.

with an insertion loss -0.255 dB at the central circulation frequency $f_0=10.629$ GHz. The transmission band extends from 2.615 to 12.97 GHz with insertion loss -1.01 and -0.595 dB, respectively. The measured absorption peak in S_{11} at 13.2 GHz due to excitation of second-order harmonic can also be identified in Fig. 1. However, the wide-band feature of the above circulator was not measured experimentally. It was realized that the internal field has to be uniformized before the real bandwidth of the circulator can be measured.⁶

Figure 2 shows the calculated scattering parameters for a six-port stripline circulator operating above FMR. This design was originally proposed by Riblet which was intended for high power wideband operation.² For this design $r=0.762$ cm, $4\pi M_1=1000$ G, $\epsilon_1=\epsilon_d=15$, $\Delta H=200$ Oe, $\tan \delta=0.0001$, and $x_1=0.508$ cm. The external field used by Riblet was 2000 Oe and the port suspension angles were $\theta_1=\theta_2=0.425$. However, we found that Riblet's design has not been optimized. After optimizing the circulation condi-

tions, Eq. (5), using H_i , θ_1 , θ_2 , and f as the independent variables we found that $\theta_1=0.35$ rad, $\theta_2=0.70$ rad, $H_i=1163$ Oe with the central transmission frequency located at 1.64 GHz (-0.56 dB insertion loss). The transmission band extends from 1.37 to 1.77 GHz and the bandwidth is about 24.4% of the transmission frequency.

Another circulator design using Riblet's parameters which may have potential applications is shown in Fig. 3. In this design $\theta_1=\theta_2=0.3$, $\epsilon_d=1$ ($\neq \epsilon_1$), and $H_i=2912$ Oe. As shown in Fig. 3 the calculated insertion loss minimum locates at 2.528 GHz with a value of -0.193 dB. The design does not show wideband operation, since the bandwidth is only about 6.1% of the transmission frequency. However, the advantage of using the design of Fig. 3 is that it is easy to be fabricated, since air can be conveniently used as the dielectric filling material providing the greatest dielectric breakdown voltage. Furthermore, it is seen in Fig. 3 that the transmission band is surrounded by two wide stopbands where the circulator becomes highly reflective (reflection loss -0.3 and -1 dB, respectively). The circulator can be thus deployed in front of a frequency selective radome which, while it is intended to transmit/receive signals at the desirable frequencies near 2.528 GHz, blocks effectively other unwanted jamming/interfering signals above and below the transmission band in wide frequency ranges to protect the electronics inside the radome.

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