Novel Ferrite Circulator Junctions with Predicted Performance

Borjak A.M. and Davis L.E.

Department of Electrical Engineering and Electronics
University of Manchester Institute of Science and Technology
P.O. Box 88, Manchester M60 1QD, United Kingdom

Abstract

New results are presented for the circulation conditions and predicted performance of a symmetrical Y ring circulator (6 GHz) and of a new asymmetrical W disk circulator (94 GHz). The latter has two ports positioned 60° away from a middle port. The components can, in principle, be more compact than conventional disk circulators.

Introduction

Circulators incorporating ferrite rings have been investigated to a lesser extent than disks[2-8]. Nagao[2,3] has investigated double-frequency operation and Dimitriyev and Davis[4,5] have derived circulation conditions and considered some novel arrangements.

The purposes of this paper are to (a) discuss the design and predicted performance of ring circulators, and (b) to introduce a new W-junction disk circulator. Both of these types of components may have some layout advantages but at the expense of a reduced bandwidth. Ring circulators require higher impedance feeder lines than disk circulators. This may obviate the need for transformers to 50Ω lines, thereby allowing a reduction in the overall size of the final component. The new W-junction circulator is asymmetrical and has two of its three ports positioned 60° away from the middle port. To have the ports located on one side of the junction in this way may have advantages in situations where the area for the circuit layout is restricted. The design and predicted performance of W circulators is discussed.

Ring Circulators

The central conductor configuration of the three-port stripline ring circulator is shown in Fig. 1. Symmetrical junctions to be treated in this paper could be obtained by setting $\phi_1 = 0$, $\phi_2 = \frac{2\pi}{3}$, $\phi_3 = \frac{4\pi}{3}$, $\psi_1 = \psi_2 = \psi_3 = \psi$, or W_i = W where

$$W_i = 2R\sin(\psi_i) \quad i = 1,\ 2,\ 3. \tag{1}$$

The magnetized ferrite rings filling the space between the central ring conductor and the ground plates have an outer radius R, an inner radius R_{in}, a relative dielectric permittivity ϵ_f, and an effective relative permeability μ_{eff}. Davis and Dimitriyev[4,5] assumed that the inner curved circumference of the ring exhibits a magnetic wall as well as the outer one. For perfect circulation between two ports to occur the remaining port must be completely isolated, therefore transmission from port 1 to port 2 is achieved by setting the input impedance at port 1 to unity. Since Z_{in1} is a complex quantity two circulation conditions therefore arise as follows:

$$\Im(Z_{in1}) = 0 \tag{2}$$

referred to as the first circulation condition, and

$$\Re(Z_{in1}) = 1 \tag{3}$$

referred to as the second circulation condition, where

$$Z_{in1} = Z_{11} - \frac{Z_{12}Z_{31}}{Z_{32}} \tag{4}$$

The impedance matrix elements for the symmetrical ring circulator have been derived, but are not included here for brevity. The circulation conditions for the main mode of circulation, (called Mode 1) for values of s = 0.2, 0.5 and 0.8, have been obtained previously[4]. These can be displayed in the usual way, i.e. for the first condition a graph of $x_2 = k_{eff}R$ vs. $\frac{\kappa}{\mu}$, and for the second condition $\frac{Z_{eff}}{Z_d}$ vs. $\frac{\kappa}{\mu}$. The actual impedance ratio[1] is given by

$$\frac{Z_{eff}}{Z_d} = \sqrt{\frac{\epsilon_d \mu_{eff}}{\epsilon_f}} = \sqrt{\frac{\epsilon_d}{\epsilon_f}\left(1 - (\frac{f_m}{f})^2\right)} \tag{5}$$

If eq. (5) is superimposed on the graph of the second circulation condition the intersection of the two curves determines the circulation frequency.

To predict the performance of a symmetrical Y ring circulator and compare it with that of a Y disk a material with $4\pi M_s = 1782$ G and $\epsilon_f = 14$ was chosen. The magnetization frequency $f_m \approx 5$ GHz. A medium of dielectric constant $\epsilon_d = 10$ was selected to surround the ferrite. If the required circulation frequency is $6GHz$ then $|\frac{\kappa}{\mu}| = \frac{f_m}{f} = 0.832$ and using eq. (5) $\frac{Z_{eff}}{Z_d} = 0.469$. From circulation conditions for the disk[1] (s = 0) and those for s = 0.2, 0.5, and 0.8 rings, it was found by interpolation and extrapolation that if s = 0 (disk) then $\psi = 0.602$ rad, if s = 0.2 (ring) ψ = 0.531 rad, and if s = 0.5 (ring) $\psi = 0.133$ rad, while if s = 0.8 (ring) it was not possible to satisfy the second circulation condition. Using each of these values of ψ and the appropriate first circulation condition, the R values obtained were : with $s = 0$, $R = 3.42$mm; with $s = 0.2$, R = 3.44 mm; and with s = 0.5, R = 2.92 mm. With these dimensions the performance of each circulator was obtained by calculating the elements of the scattering matrix [S] using the following transformation

LL

$$[S] = \frac{[Z]-[I]}{[Z]+[I]} \quad (6)$$

in which [Z] is the impedance matrix and [I] is the 3×3 unity matrix. Figs. 2, 3 and 4 show the reflection coefficient s_{11}, the isolation coefficient s_{31}, and the transmission coefficient s_{21}, of the disk, and the s = 0.2 and s =0.5 rings, respectively. It can be seen that the disk exhibits the widest bandwidth. The insertion loss spike that occurs with the disk, due to the $n = \pm 2$ terms in the field expansion, becomes wider with the s = 0.2 ring, and very wide with the s = 0.5 ring.

Figs. 2, 3 and 4 do not necessarily represent optimum performance and further work is in hand.

Asymmetrical W disk Circulators

The newly proposed W stripline disk circulator is shown in Fig. 5. The conditions for circulation from port 1 to port 2 and from port 3 to port 1 are identical and are shown in Fig. 6(a,b). The conditions for circulation from port 2 to port 3 are shown in Fig. 7(a,b). Circulation conditions for transmission 2→ 3 and 3 → 1 resemble equation (2) and (3) with Z_{in2} and Z_{in3} in place of Z_{in1}.

Z_{in2} and Z_{in3} are given by :

$$Z_{in2} = Z_{22} - \frac{Z_{12}Z_{23}}{Z_{13}} \quad (7)$$

and

$$Z_{in3} = Z_{33} - \frac{Z_{31}Z_{23}}{Z_{21}} \quad (8)$$

The maximum coupling angle allowed for the W-disk is $\psi_{max} = \frac{\pi}{6} = 0.52$ rad. As can be seen from Figs. 6(b) and 7(b) the impedance ratios are negative and so circulation will occur in the opposite sense from that indicated in Fig. 5. These Mode 1 circulation conditions are restricted to $|\frac{\kappa}{\mu}| < 0.5$, and therefore the circulation frequency must be at least $2f_m$.

To explore the predicted performance of these W-circulators, a ferrite with $4\pi M_s = 5000$ G and $\epsilon_f = 12.5$ was chosen. The surrounding dielectric medium was selected to be quartz, $\epsilon_d = 4.4$, and the circulation frequency 94 GHz. The design procedure described above was followed with the two sets of circulation conditions shown in Figs. 6 and 7, and each resulted in different dimensional data, R and ψ, as listed in Table 1. The predicted performance of design A is shown in Fig. 8(a) and of design B is shown in Fig. 8(b), with the input at each port in turn. It can be seen that the insertion loss, isolation and reflection loss are well aligned when the input is at port 1 and the output at port 3. When the input is at port 2 or port 3, the reflection loss or the isolation is misaligned (off frequency). It is not known yet whether the design parameters can be adjusted to produce improved frequency alignment.

Design A based on 1→2 Conditions	
R in mm →	0.277
ψ in radian →	0.219
Design B based on 2→3 Conditions	
R in mm →	0.281
ψ in radian →	0.248

Table 1: Disk Data for The W disk

Conclusion

The symmetrical Y ring circulator exhibits a narrower bandwidth than that of the symmetrical Y disk circulator. However, in general the outer radius of the ring and the coupling angle are smaller than those required for the disk and therefore, in applications where broad bandwidths are not required, a ring circulator may provide a more compact component without the need for matching transformers.

The asymmetrical W disk circulator is a novel structure which provides opportunities for a more compact layout than a Y circulator in some circumstances. Circulation between the ports separated by 240° provides s-parameters that are well-aligned with the design frequency. Circulation between the other two ports shows some misalignment. An immediate application of a W disk structure would be as a compact iso-circulator with a matched load on the middle port.

References

[1] Wu Y.S. & Rosenbaum F.J., "Wideband Operation of Microstrip Circulators", IEEE Trans. Microwave Theory & Techniques vol MTT-12,Oct 1974 pp 849-856.

[2] Nagao T., "Double Circulation Frequency Operation of Stripline Y-Junction Circulators", IEEE Trans. Microwave Theory & Techniques vol MTT-25 No 3 March 1977, pp 181-189.

[3] Nagao T., "Broad-Band Operation of Stripline Y Circulators", IEEE Trans. Microwave Theory & Techniques vol MTT-25 No 12 Dec. 1977, pp 1042-1047.

[4] Davis L.E. & Dimitriyev V., "Nonreciprocal Devices Using Ferrite Ring Resonators", Proc IEE, Part H to be published.

[5] Dimitriyev V., "Ferrite Circulators with ring resonators". Published in "Computer-Aided Design of Microwave Devices and Systems". Moscow Institute of Radio Electronics and Automation (MIREA) 1982, 15 pp.

[6] Wu Y.S. & Rosenbaum F.J., "Mode Chart for Microstrip Ring Resonators", IEEE Trans. Microwave Theory & Techniques, Vol MTT-21 July 1973. pp 487-489

[7] Helszajn J., Nisbet W.T. & Sharp J., "Mode Charts of Gyromanetic Planar Ring Resonators", Electronics Letters 19th Nov 1987 Vol. 23 No 24. pp 1290-1291

[8] Orlando A.J.F. and Stumpf R.M.O. , "Annular Ferrite Circulator in Stripline Technology" 21st European Microwave Conference, Stuttgart, Germany, Sept. 1991, Proceedings, Vol. 2, pp 1159-1164.

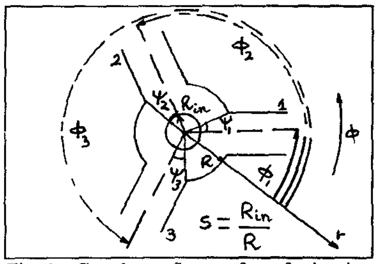


Fig. 1 - Coordinate System for a ferrite ring Y circulator

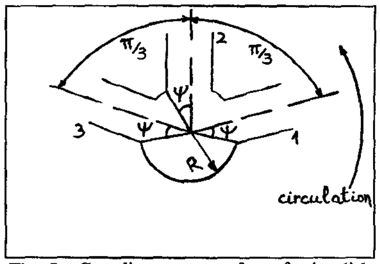


Fig. 5 - Coordinate system for a ferrite disk W circulator

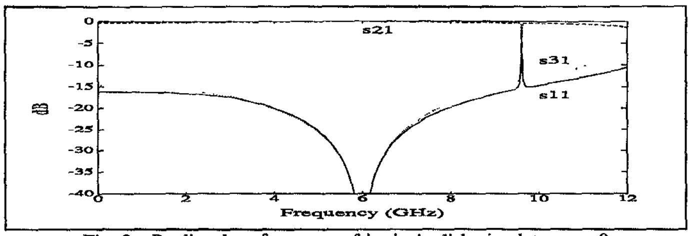


Fig. 2 - Predicted performance of intrinsic disk circulator, s = 0
Parameters given in text

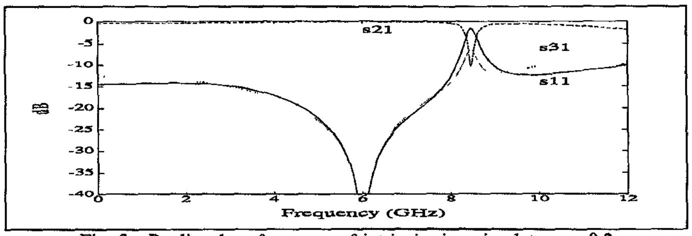


Fig. 3 - Predicted performance of intrinsic ring circulator, s =0.2
Parameters given in text.

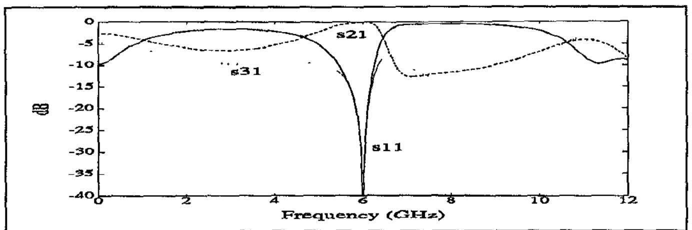
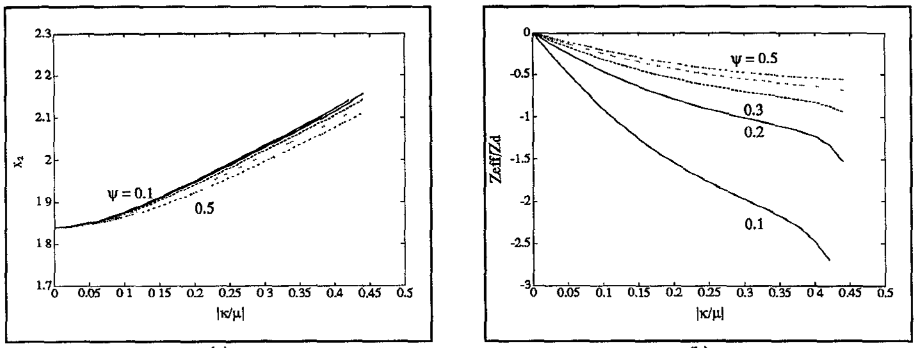
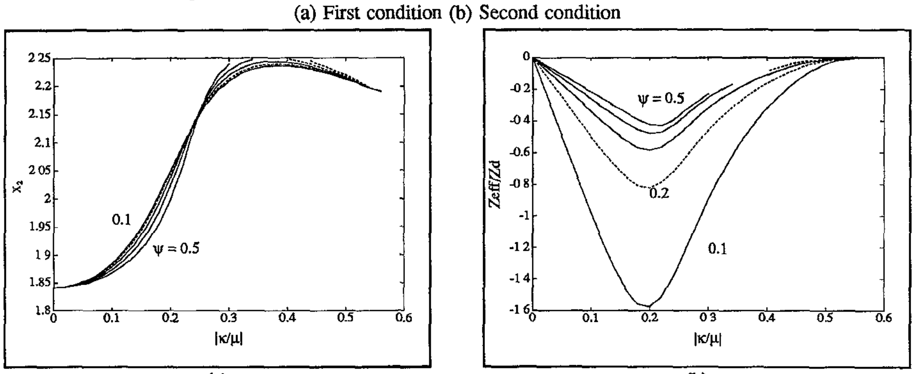


Fig. 4 - Predicted performance of intrinsic ring circulator, s = 0.5
Parameters given in text.



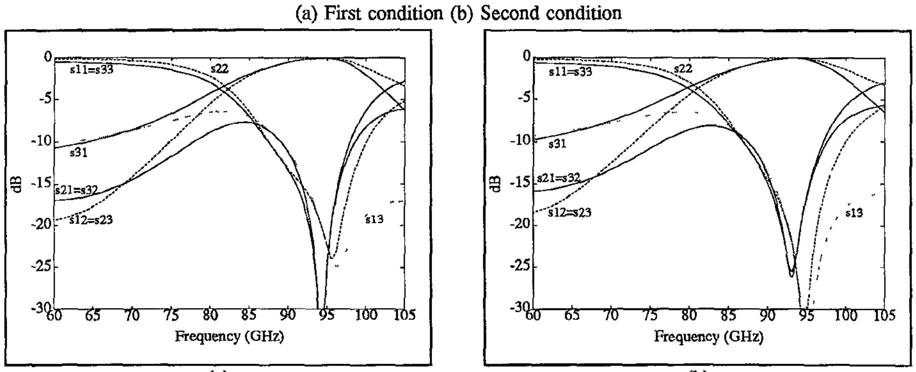
(a) (b)

Fig. 6 - Conditions for circulation from ports 1 to 2 and ports 3 to 1.
(a) First condition (b) Second condition



(a) (b)

Fig. 7 - Conditions for circulation from ports 2 to 3.
(a) First condition (b) Second condition



(a) (b)

Fig. 8 - Predicted performance of an intrinsic 94 GHz W-disk circulator.
(a) Using conditions in Fig. 6(a,b);
(b) Using conditions in Fig. 7(a,b).
Design parameters given in text.