Mode 1 and Mode 2 Designs for 94-GHz Microstrip Circulators

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Abstract— **Details are given of two theoretical designs for a 94 GHz ferrite circulator in a quartz substrate, based on circulation modes 1 and 2, and their predicted performances are described. The 15-dB isolation bandwidths are 8 GHz and 3 GHz, respectively. The narrower bandwidth design has a larger ferrite radius, and this may provide some mechanical advantages in manufacturing. Other comparisons are made.**

I. Introduction

CIRCULATION in a symmetrical three-port ferrite disk can occur in a number of different "circulation modes". These were labeled Mode 1, 1A, 2, etc., by Davies and Cohen [2], and subsequently the possibility of using Mode 1 to design a "*tracking circulator*" with a broad bandwidth was pointed out by Wu and Rosenbaum [1]. Ferrites with values of saturation magnetisation required to obtain tracking behavior at frequencies higher than approximately 28 GHz [3] are not available, and therefore all ferrite junction circulator designs are likely to exhibit narrow bandwidths at 94 GHz. An additional problem is the small ferrite radius required, and therefore, the manufacturing tolerances together with the narrow bandwidth may cause production difficulties. The purpose of this note is to provide some preliminary design data to illustrate a choice between ferrite size and bandwidth.

II. Discussion

The circulation conditions of the Y-disk circulator for Mode 2 are shown in Figs. 1 and 2 in more detail than have been previously given in [2] and it can be seen that 1) the values of kR in Fig. 1 are larger than those of Mode 1 [1] and virtually independent of ψ, and 2) the values of $\frac{Z_{eff}}{Z_d}$ in Fig. 2 are negative whereas those of Mode 1 [1] are positive. The larger values of kR indicate that the ferrite radius can be larger using Mode 2, and the negative impedance ratio means that the direction of circulation is opposite to that in Mode 1. It should be noted that the circulation conditions in Figs. 1 and 2 are shown over the restricted $0 < \frac{\kappa}{\mu} < 0.4$. When operating at high frequencies such as 94 GHz it may be advantageous to make R as large as possible, and therefore a design based on Mode 2 may be preferable.

III. Results

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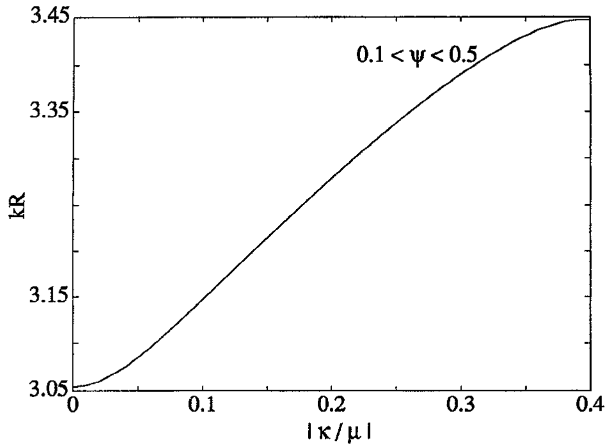

Fig. 1. Mode 2 first circulation condition of the Y-disk circulator.

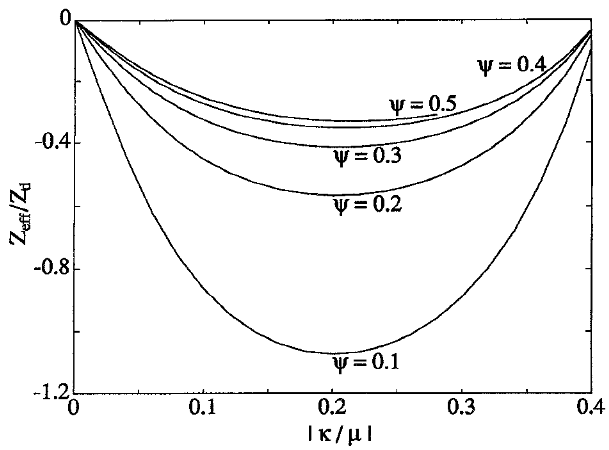

Fig. 2. Mode 2 second circulation condition of the Y-disk circulator.

A ferrite material with $4\pi M_s = 5000$ Gauss and $\epsilon_f = 12.5$ was chosen to operate at $f = 94$ GHz. Quartz with $\epsilon_r = 4.4$ was selected to be the dielectric surrounding the ferrite. From the usual equations [1] $\frac{\kappa}{\mu} = 0.149$, and $\frac{Z_{eff}}{Z_d} = 0.587$. Therefore, the curve in the second circulation condition corresponding to $\psi = 0.254$ rad for Mode 1 and $\psi = 0.181$ rad for Mode 2 matches the same impedance ratio. The circulator radius can be calculated from the first circulation condition curves for the previous ψ values that yield $R = 0.270$ mm for Mode 1 and $R = 0.467$ mm for Mode 2. These results are summarized in Figs. 3 and 4. The predicted reflection coefficient s_{11}, and isolation and transmission coefficients, i.e., s_{31} and s_{21} for Mode 1 and s_{21} and s_{31} for Mode 2, are shown

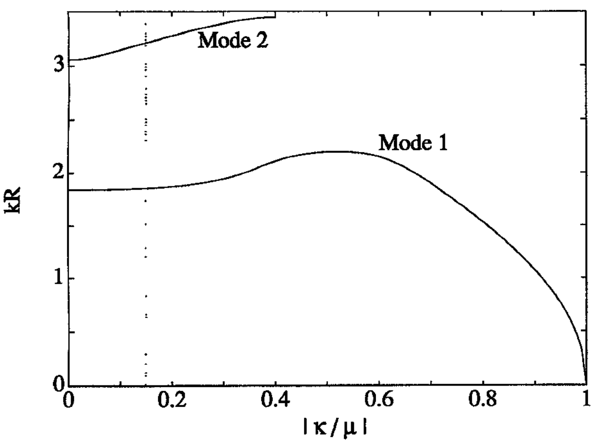

Fig. 3. First circulation condition for Mode 1 ($\psi = 0.254$ rad) and Mode 2 ($\psi = 0.181$ rad). The value of $\frac{\kappa}{\mu} = 0.149$ is indicated (· · ·).

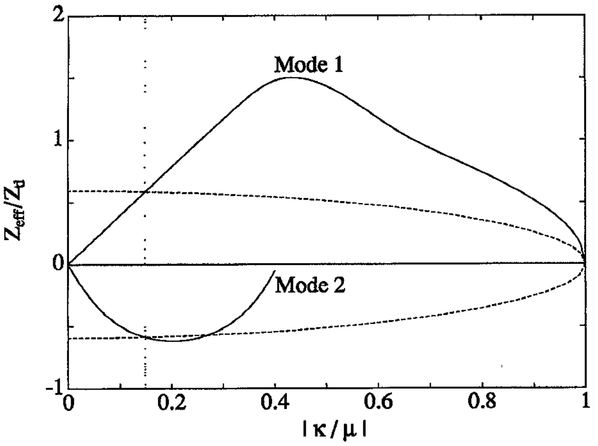

Fig. 4. Second circulation condition for Mode 1 ($\psi = 0.254$ rad) and Mode 2 ($\psi = 0.181$ rad). The curves of $\pm\frac{Z_{eff}}{Z_d}$ for $\epsilon_d = 4.4$ and $\epsilon_f = 12.5$ are shown (- - -) and the value of $\frac{\kappa}{\mu} = 0.149$ is indicated (· · ·).

in Fig. 5 over a frequency range 60–100 GHz. It can be seen in Fig. 5 that at the level of -15 dB isolation Mode 1 and Mode 2 exhibit bandwidths of 8 GHz and 3 GHz, respectively.

Now, let us consider the strip widths required for these two designs. Although Fig. 1 might suggest that Mode 2 designs are insensitive to ψ, Fig. 2 indicates that a specific value of ψ is required to obtain the correct impedance ratio. The strip width is given by $W = 2R\sin\psi$, and for the Mode 1 and Mode 2 designs previously obtained the required strip widths are 0.136 mm and 0.168 mm, respectively. To determine whether quarter-wave transformers are required it is necessary to calculate the $\frac{W}{h}$ ratio required for a microstrip with a characteristic impedance $Z_o = 50\ \Omega$ and using $\epsilon_r = 4.4$, where h is the substrate thickness. From [4], it can be shown that $\frac{W}{h} = 1.912$, and hence it follows that impedance transformers can be avoided by selecting $h = 0.071$ mm for the Mode 1 design, or $h = 0.088$ mm for the Mode 2 design. These thin substrates may be too fragile or increase the attenuation to an unacceptable level, and therefore a thicker substrate may be preferred. If a thickness of 0.120 mm is selected [5], the Mode 1 and Mode 2 designs yield characteristic impedance values of $Z_{o1} = 66.4\ \Omega$ and $Z_{o2} = 59.4\ \Omega$, respectively, and hence

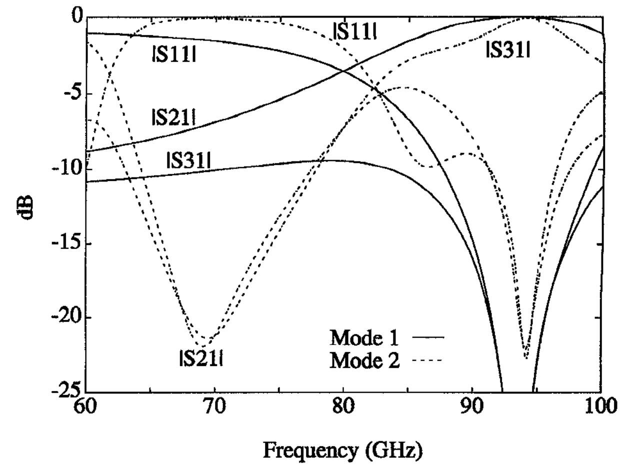

Fig. 5. Predicted performance of the ferrite Y-disk circulator using Mode 1 ($R = 0.270$ mm, $\psi = 0.254$ rad) (- - -) and Mode 2 ($R = 0.467$ mm, $\psi = 0.181$ rad) (——).

TABLE I
COMPARISON OF DESIGNS USING MODE 1 AND MODE 2.

Modes →	Mode 1	Mode 2
R (mm) →	0.270	0.467
ψ (rad) →	0.254	0.181
B.W. (GHz) (15 dB isolation) →	8	3
W (mm) →	0.136	0.168
h (mm) (for 50Ω) →	0.071	0.088
Z_o (Ω) (for h = 0.12 mm) →	66.4	59.4

Center frequency: 94 GHz. Quartz substrate: $\epsilon_r = 4.4$.

single-section transformers may be required depending on the system specification. These data are summarized in Table I for easy comparison.

IV. CONCLUSION

Two theoretical designs for a 94 GHz microstrip circulator on a quartz substrate have been presented for the first time. Due to the lack of a ferrite with a sufficiently high value of saturation magnetisation, both designs have inherently narrow bandwidth. The design based on Mode 1 circulation conditions has a -15 dB isolation bandwidth of 8 GHz, and the Mode 2 design 3 GHz. It has been shown that by selecting the substrate thickness correctly, the need for transformers is avoided and an intrinsically small circulator is obtained. For the Mode 1 or Mode 2 design, the thickness required is 71 μm or 88 μm, respectively. Thus, the smaller disk requires a thinner substrate and gives a broader bandwidth; the larger disk requires a thicker substrate and gives a narrower bandwidth. If a larger value of substrate thickness is required, e.g., $h = 120\ \mu$m, the intrinsic designs yield $Z_{o1} = 66.4\ \Omega$ and $Z_{o2} = 59.4\ \Omega$, respectively, and the introduction of a single-section transformer is desirable. If there is insufficient area to permit a transformer on each port, the Mode 2 design offers the smaller mismatch at the design frequency. It is clear that computer-aided design techniques can be useful in considering the trade-offs in the microwave and mechanical design, particularly at these short wavelengths.

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