WIDEBAND OPERATION OF MICROSTRIP CIRCULATORS

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Abstract

Octave bandwidths are found to be readily obtainable in 3-port Y-junction microstrip circulators. Theoretical and experimental results are presented which show that wide coupling lines and a smaller than usual disk radius can be used to obtain wideband operation.

Microstrip junction circulators are usually designed according to the stripline theory of Bosma[1] and of Fay and Comstock[2] with minor modifications[3] to account for fringing at the edge of the microstrip disk resonator. The resulting three port junction resonator is often impedance matched with quarter-wave transformers[2,4] to obtain wide operating bandwidths. In this paper Bosma's results are extended to show that wide bandwidth is inherently obtainable from microstrip junction circulators provided that they are operated in the range of large $|\frac{\kappa}{\mu}|$ and that they are coupled to wide lines at the junction.

In Bosma's theory two conditions for perfect circulation (infinite isolation of one port) are developed. One yields the resonance frequencies for the uncoupled disk resonator; the other gives the impedance relation, at resonance, that satisfies the boundary conditions of the coupled resonator. For below resonance operation and assuming that only the dominant (n=1) mode is significant the usual design equations are written

$$SR = 1.84 \qquad (1)$$

$$\sin\psi = \frac{\pi Z_d}{\sqrt{3}\,(1.84)\,Z_{eff}}\left(-\frac{\kappa}{\mu}\right) \qquad (2)$$

where

$S = \frac{\omega}{c}\sqrt{\mu_{eff}\varepsilon_f}$ = radial propagation constant in disk,

R = disk radius

ω = radian microwave frequency

c = speed of light in vacuum

$Z_d = \frac{120\pi}{\sqrt{\varepsilon_d}}\,\Omega$ = wave impedance in region outside resonator,

$Z_{eff} = 120\pi\sqrt{\frac{\mu_{eff}}{\varepsilon_f}}\,\Omega$ = wave impedance in ferrite loaded disk,

2ψ = angle subtended by the coupled lines at the disk edge,

and ε_d, ε_f, are the relative permittivities of the outside region and the ferrite, respectively. The ferrite is described by its permeability tensor elements κ, and μ, and

$$\mu_{eff} = \frac{\mu^2 - \kappa^2}{\mu}\,.$$

If the ferrite is magnetized to saturation they are the Polder tensor elements.[5] If the ferrite is partially magnetized, the results of Schlömann[6] and of Green[7,8] et. al. may be used.

Equation 1 is valid for small values of $|\frac{\kappa}{\mu}|$. Figure 1 shows the dependence of SR on $|\frac{\kappa}{\mu}|$ for several coupling angles, obtained by including the first three terms in Bosma's Green's function expansion.[9] These solutions are denoted by Mode 1-. The dashed lines represent the non-degenerate resonances of the uncoupled disk resonator. Another set of solutions (1+) is also shown which is seldom employed since larger values of SR would be needed in an actual circulator.

Notice that, in principle, circulation could be obtained between $0 \le SR \le 1.84$ if the second circulation condition on impedance matching can be satisfied.

The normalized junction wave impedance, obtained by substituting the roots displayed in Figure 1 into the second circulation condition,[9] are shown in Figure 2 for various coupling angles. This ratio is zero at $|\frac{\kappa}{\mu}|=1$.

Now Z_{eff}/Z_d is also explicitly defined as

$$\frac{Z_{eff}}{Z_d} = \sqrt{\frac{\varepsilon_d}{\varepsilon_f}}\left[\frac{\mu^2 - 2}{\mu}\right]^{\frac{1}{2}} \qquad (3a)$$

$$\simeq \sqrt{\frac{\varepsilon_d}{\varepsilon_f}}\left[1 - \left(\frac{\kappa}{\mu}\right)^2\right]^{\frac{1}{2}} \qquad (3b)$$

provided that μ does not deviate from unity significantly. Figure 3 shows this result compared with the ψ=0.2 rad. curve from Figure 2 for the case $\varepsilon_d=\varepsilon_f$. Their intersection near $|\frac{\kappa}{\mu}|\simeq 0.2$ corresponds to SR=1.84 and is typical of a direct coupled (narrow band) circulator design.

Figure 4 shows Z_{eff}/Z_d from Eq. (3b) along with the result from the second circulation condition for the case of a wide coupling angle; ψ=0.51 rad. The two functions now overlap over a large frequency range as seen in Figure 5. This result implies that by using a wide coupling angle and a small disk resonator (SR≃1.2) wide band circulation should be obtained. The expected bandwidth is of the order $\Delta f \simeq (2.8\text{ MHz/Oe})(4\pi M_s)$, where $4\pi M_s$ is the saturation magnetization of the ferrite. We term this the Continuous Tracking Circulator (CTC).

Impedance matching is, of course, still required in order to connect the wide junction to the usual 50Ω microstrip lines. Figure 6 shows a sketch of an experimental CTC conductor pattern. Linearly tapered transformers were used to mechanically connect the 50Ω input lines to the resonator. In this design $\psi\simeq 0.525$ rad.; R=0.100". The center frequency was 9 GHz. A 1"x3/4"x0.025" substrate of TT1-390 material ($4\pi M_s$=2150 G) was used. Thus the expected bandwidth is about 6 GHz centered at 9 GHz.

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Experimental results are shown in Figure 7a. The upper figure is the isolation between 5.5 GHz and 15.0 GHz measured for each port, sequentially. Isolation of at least 10 dB is noted in the range 6.75 GHz to 14 GHz, approximately one octave, and somewhat more than the expected 6 GHz bandwidth. The isolation is better at mid-band.

The insertion loss is shown in Figure 7b for each port, sequentially. It is about 1 dB over most of the X-band, rising to about 2 dB at 7.25 GHz and 12.4 GHz. The large absorption shown near 13.2 GHz is caused by radiation from the biasing magnet located above the circulator disk. The device was biased with 0.2" diameter magnets, about 3/8" tall.

These preliminary results suggest that microstrip Y-junction circulators with bandwidths of the order (2.8 MHz/Oe)$(4\pi M_s)$ can be readily fabricated simply by choosing the appropriate (wide) coupling angle and disk radius ($SR \approx 1.2$) and then suitable connecting to the 50Ω input lines. The isolation obtainable over the band will depend on the impedance characteristics of the transformers chosen, on the quality of the terminations and connectors, and on the size and homogeneity of the biasing magnets, as is the case for any circulator.

Acknowledgments

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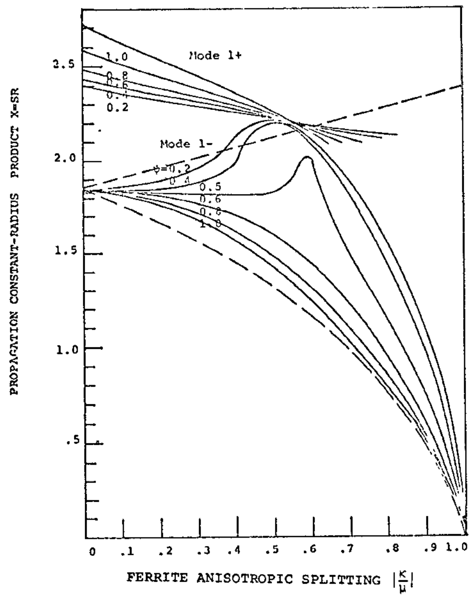

FIG. 1 PERFECT CIRCULATION ROOTS OF THE FIRST CIRCULATION CONDITION FOR VARIOUS COUPLING ANGLES (3RD ORDER)

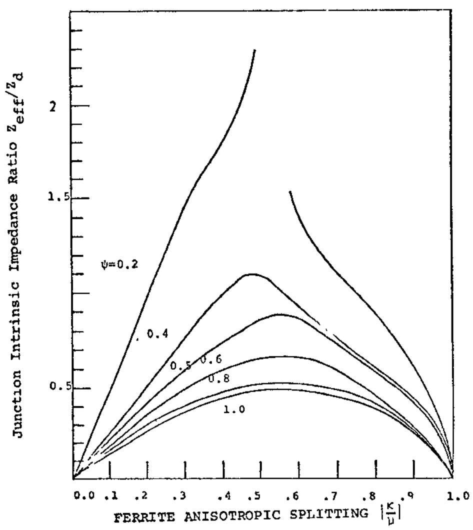

FIG. 2 NORMALIZED JUNCTION IMPEDANCE RATIO AS A FUNCTION OF ANISOTROPIC SPLITTING CALCULATED FROM THE SECOND CIRCULATION CONDITION FOR VARIOUS COUPLING ANGLES.

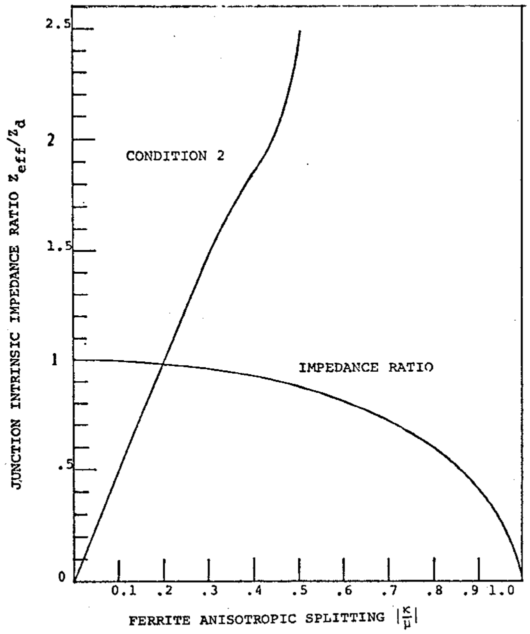

FIG. 3 DIRECT COUPLED CIRCULATOR NORMALIZED JUNCTION IMPEDANCES.

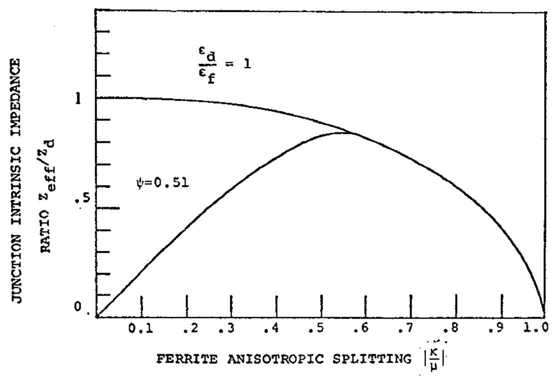

FIG. 4 CONTINUOUS TRACKING CIRCULATOR (CTC) NORMALIZED JUNCTION IMPEDANCES.

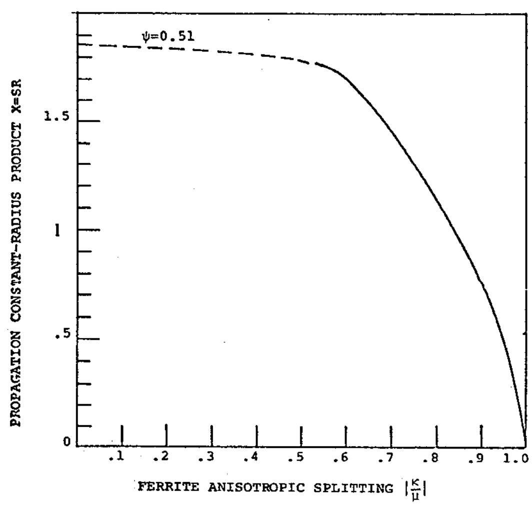

FIG. 5 OPERATING RANGE OF A CONTINUOUS TRACKING CIRCULATOR.

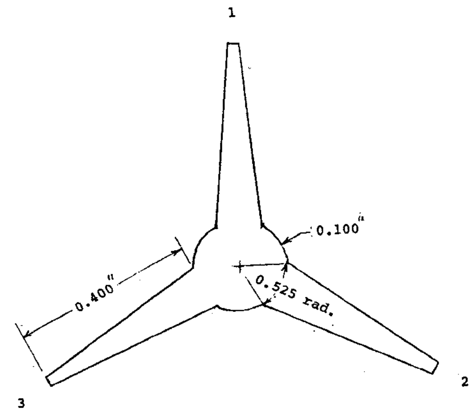

FIG. 6 SAMPLE CONDUCTOR PATTERN FOR CTC.

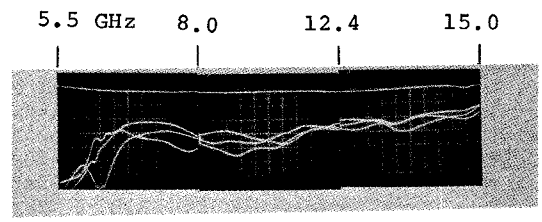

FIG. 7a ISOLATION: SCALE:5dB/DIV

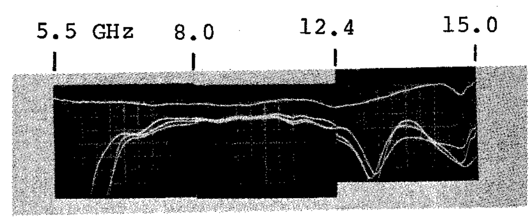

FIG. 7b INSERTION LOSS: SCALE: 1 dB/DIV.

FIG. 7 MEASURED ISOLATION AND INSERTION LOSS OF CTC.