ANALYSIS OF WIDE-BAND MICROSTRIP CIRCULATORS
BY POINT-MATCHING TECHNIQUE

A. M. Khilla

University of Duisburg
Duisburg, West Germany

ABSTRACT

An exact field theory treatment of microstrip Y-junction circulators for wideband operation is presented. Field expressions are written in each region of the junction in form of infinite summation of the corresponding region modes. Matching of the fields at the common boundaries, taking fringing fields in microstrip structures into account, leads to a set of infinite non-homogeneous equations in these mode-amplitudes. A wideband microstrip circulator, designed using the point-matching technique, is observed. The 20-dB isolation bandwidth is about 62 % without using any external tuning elements.

Introduction

An octave bandwidth design of a disc-shaped microstrip circulator was proposed by Wu and Rosenbaum 1974 [1] whose analysis was based upon Bosma's Green function method [2]. Experimentally they predicted a wideband operation of a designed microstrip circulator and found that the average isolation and insertion loss were about 15-dB and 1.5-dB, respectively. Ayasli [3] further examined Wu and Rosenbaum's design. He found that the Green function suitable to the integral equation method is not unique but it can be chosen from a certain class of functions. The all previous analysis neglected the fringing field effect of the microstrip structures. The effect of the fringing fields are significant in stripline circuit analysis even more significant in microstrip circuit analysis, e.g. [4] - [10].

In this paper, a field theory treatment of microstrip circulators for wideband operation including the effects of the fringing fields in these geometries is presented. The optimum shape and dimensions of a microstrip circulator for wideband operation without using any external tuning elements is investigated.

Theoretical Analysis

For a junction geometry shown in Fig. 1 and when the thickness of the substrate is much less than the wavelength, the electromagnetic fields in the junction can be taken as independent of z. A complete expansion for the electric field in the ferrite region takes the following form:

$$E_z^f(r,) = \begin{cases} \sum_{n=-\infty}^{\infty} a_n J_n(k_f r) e^{-jn\varphi}, & \mu_{eff} > 0 \\ \sum_{n=-\infty}^{\infty} a_n I_n(k_f r) e^{-jn\varphi}, & \mu_{eff} < 0 \end{cases} \quad (1)$$

where $k_f = \omega\sqrt{\varepsilon_0\mu_0\varepsilon_f\mu_{eff}}$ and $\mu_{eff} = (\mu^2 - k^2)/\mu$.

The coefficients a_n are the unknown field amplitudes, $J_n(x)$ and $I_n(x)$ are the first kind and the modified first kind n^{th} -order Bessel function, respectively. From Maxwell's equation, the radial and azimuthal magnetic field components can be obtained.

Excitation by the dominant TEM mode is assumed to take place at only one of the ports (assume port 1). The incident electric field at port 1 is given by:

$$E_z(x_1, y_1) = e^{-jk_o x_1} , \quad \text{where } k_o = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_d} . \quad (2)$$

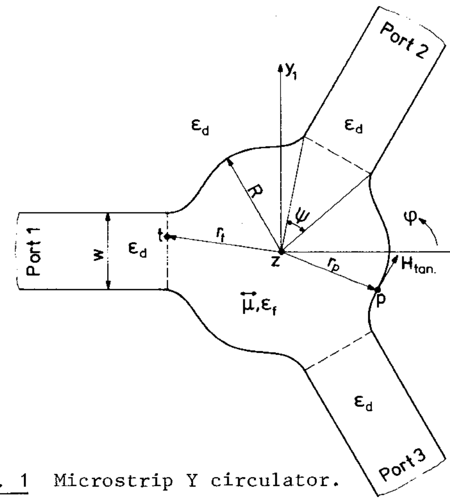

Fig. 1 Microstrip Y circulator.

The junction presents a discontinuity to the incident fields, therefore reflected waves are induced at the discontinuities. In general, the reflected electric field in the i^{th} port can be written as:

$$E_z^i(x_i, y_i) = \sum_{m=0}^{\infty} d_m^i \cos[(1+2y_i/w)m\pi/2] \, e^{k_m x_i} , \quad (3)$$

where $k_m = \sqrt{(m\pi/w)^2 - \omega^2\mu_0\varepsilon_0\varepsilon_d}$.

To calculate the circulator performances, the boundary conditions must be satisfied. The point-matching technique [11] - [12] is applied to match the fields at the boundaries between the different regions. Almost at the periphery where the coupling ports are absent, the magnetic field tangential to the periphery is to be zero this boundary condition can be applied at any point p ($r = r_{pe}$, $\varphi = \varphi_p$) at the periphery. The radius r_{pe} is the effective value of the radius r_p considering the fringing field effect.

$$H_{tan.}(r_{pe} \cdot \varphi_p) = 0 . \quad (4)$$

The continuity condition for the tangential electric and magnetic fields can be applied at any point t ($r = r_{te}$, $\varphi = \varphi_t$) along the periphery on each port to give:

$$E_z^f(r_{te}, \varphi_t) = \delta_{1i} E_z(x_{1t}, y_{1t}) + E_z^i(x_{it}, y_{it}) . \quad (5)$$

$$H_{tan.}^f(r_{te}, \varphi_t) = \delta_{1i} H_{tan.}(x_{1t}, y_{1t}) + H_{tan.}(x_{it}, y_{it}) . \quad (6)$$

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It is to be noted that since i = 1,2, and 3 (3-port), equs. (4), (5), and (6) represent nine non-homogeneous equations. Since the unknown involved in these equations are infinite, an infinite number of equations is required to obtain an exact solution. Truncation must be done to solve these equations numerically.

Fringing Field Approximation

An equivalent-waveguide representation [13] - [15] allows a microstrip line of width w and imperfect magnetic walls to be replaced by a parallel-plate waveguide model. It consists of two perfectly conducting plates having a frequency-dependent effective width $w_{eff}(f)$ and magnetic sidewalls. The plates are separated by the substrate thickness h, and filled with a frequency dependent effective relative permittivity $\varepsilon_{eff}(f)$ [7].

The effective values of the parallel-plate-waveguide model are:

$$\varepsilon_{eff}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}(0)}{1+G\cdot(f/f_p)^2} \qquad (7)$$

$$w_{eff}(f) = \frac{120\,\pi\,h}{Z_0(f)\cdot\sqrt{\varepsilon_{eff}(f)}} \qquad (8)$$

where $f_p = z_0(0)/(2\mu_o h)$.

$\varepsilon_{eff}(0)$ is the static value of the effective relative permittivity proposed by Hammerstad [7].

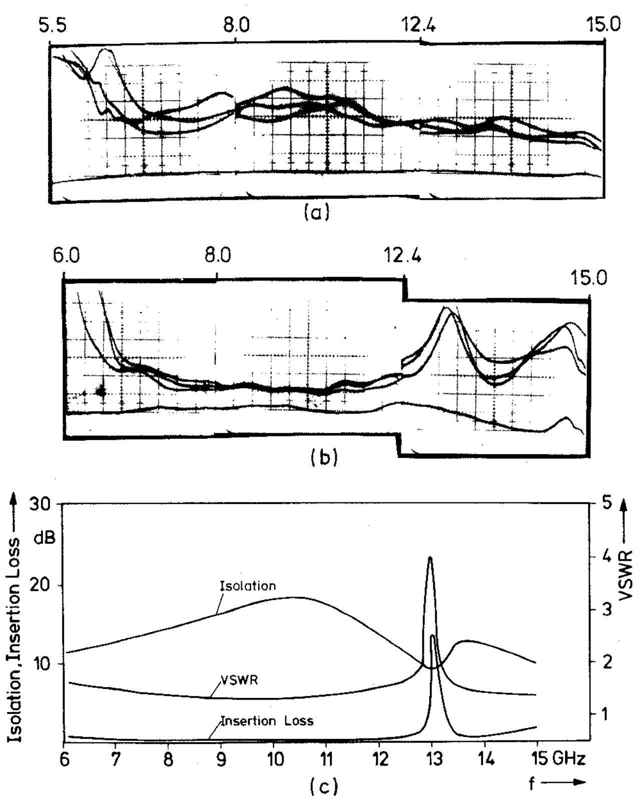

Fig. 2 a) Isolation of an experimental continuous tracking circulator (5-dB/div.) [1],

b) Insertion loss of an experimental continuous tracking circulator (1-dB/div.)[1],

c) Computed performance of this circulator, this theory.

Numerical Results

Next, this method is applied to analyse the proposed wideband circulator design of Wu and Rosenbaum, whose design data are given in [1]. Fig. 2 shows the calculated performances of Wu and Rosenbaum's proposed design and the reported experimental results [1]. The agreement between the calculated performances and the experimental results [1] is good. The calculated average insertion loss 0.3-dB, however, is smaller as experimentally detected. The degradation in the performances at the junction about 13.2 GHz is present in both results and is investigated here as the resonant frequency of the TM_{210} mode of the disc resonator.

The performances of Y-junction microstrip circulators employing disc as well as triangular resonators are examined using this method described here in order to give design data for the possible wideband operation of each geometry. In the numerical optimization, the three parameters such as ε_d, R, and ψ are optimized for the ferrite material TT1-390. The optimum design data are reported here.

Circulators Employing Disc Resonators

The two parameters R and ψ are optimized for an optimum wideband operation in the case of $\varepsilon_f = \varepsilon_d$. Fig. 3 shows the computed circulator performances.

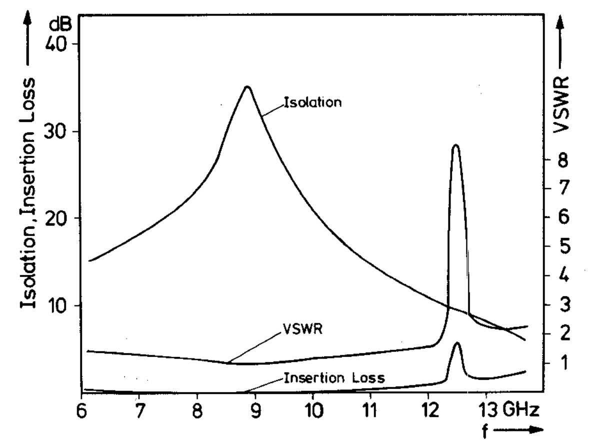

Fig. 3 Computed performance of a disk-shaped circulator on ferrite substrate.

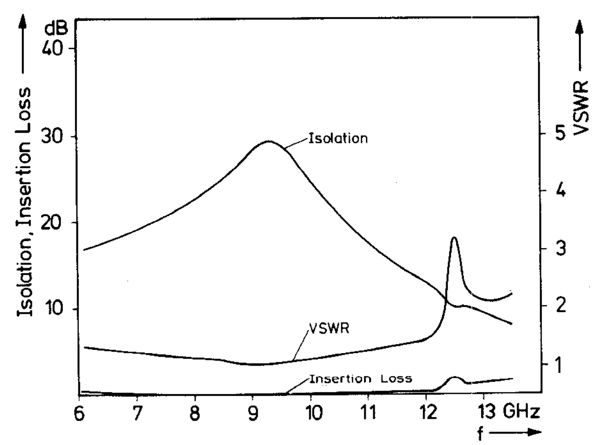

Fig. 4 Computed performance of the best disk-shaped curculator (ε_d = 1.34 ε_f).

It is found that ψ of about 0.85 rad. gave the optimum 20-dB isolation bandwidth of 31 %. The operation range is $0.89 < k_f R < 1.69$, where R is the disc radius. Now, the three parameters R, ψ, and ε_d are optimized for an optimum operation. Fig. 4 shows the computed optimum performances. The ratio $\varepsilon_d/\varepsilon_f$ of 1.34 and a coupling angle ψ of 0.7 rad. are found to give an optimum 20-dB isolation bandwidth of 36.5 %. The operation range is $0.86 < k_f R < 1.82$.

Circulators Employing Triangular Resonators

The radius of the inscribed circle of the triangular resonator is designated as R. Fig. 5 shows the circulator performance employing triangular resonator for an optimum operation in case $\varepsilon_d = \varepsilon_f$. A coupling angle ψ of 0.6 rad. gave the optimum 20-dB isolation bandwidth of 49 %. The operation range is $0.41 < k_f R < 1.56$. ε_d is now taken as a parameter to be optimized. Fig. 6 shows the optimum computed circulator performances in the case $\varepsilon_d \neq \varepsilon_f$. The ratio $\varepsilon_d/\varepsilon_f$ of 1.34 and a coupling angle ψ of 0.6 rad. are found to give a 20-dB isolation bandwidth of 62 %. The operation range is $0.28 < k_f R < 1.89$.

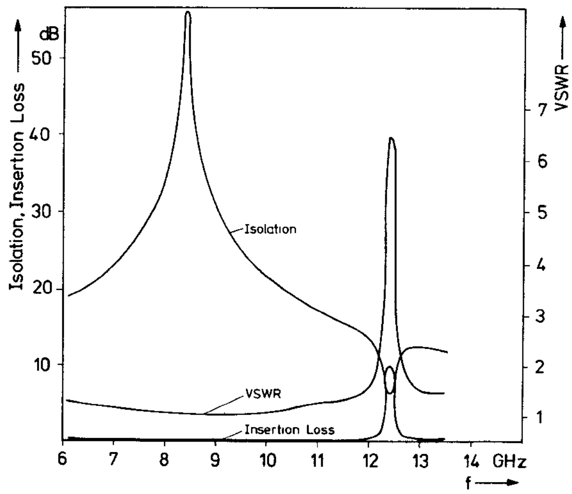

Fig. 5 Computed performance of a triangular circulator on ferrite substrate.

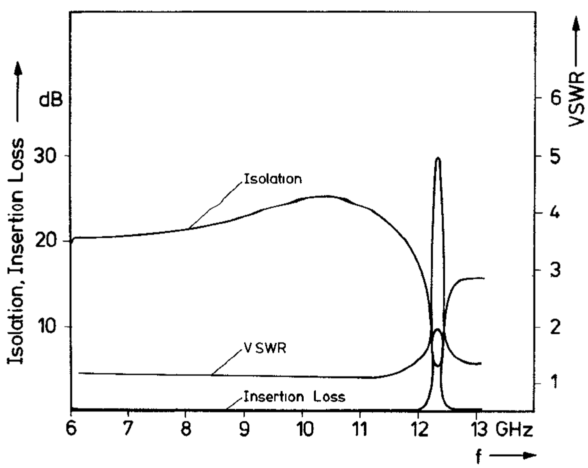

Fig. 6 Computed performance of the best triangular circulator ($\varepsilon_d = 1.34\ \varepsilon_f$).

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