Novel Filter Design Incorporating Asymmetrical Stripline Y-Junction Circulators

H. How, C. Vittoria, *Fellow, IEEE*, and C. Carosella

***Abstract*—Theoretical treatments of an asymmetrical stripline Y-junction circulator have been carried out. These include a formulation of the circulation conditions of an asymmetrical circulator as well as its transmission characteristics under wide-frequency-band consideration. We found that filter designs incorporating circulators are very plausible, which give rise to a narrow transmission band around the desired transmission frequency and a wide stopband extending many times the fundamental transmission frequency. In our design higher order mode excitations inherent in other filter designs are attenuated. In addition, owing to the off-resonance operation of the ferrites, our design could be applied under higher power conditions than traditional resonant ferrite filters.**

I. Introduction

A circulator is defined as a device with ports arranged such that energy entering a port is coupled to an adjacent port but not to the third port. The first commercial microwave circulator appeared in the early 1950's, while a full theoretical account of its operation was not published until 1962 [1], [2]. Fay and Comstock presented a working model for a symmetrical Y-junction circulator based on the splitting of the two counterrotating dipole modes of the ferrites in the presence of a biasing field [3]. The "continuous frequency tracking" conditions for a wide-band junction circulator were developed by Wu and Rosenbaum [4], and the construction of wide-band circulators with low insertion loss and low return loss was discussed by various authors [5]–[7]. All of the traditional circulator designs make use of the nonreciprocal property of the ferrites, accentuated on the isolation feature of the device under wide (transmission) frequency band and low-insertion-loss applications. We explore in this paper the possibility of another potential use of circulators, in which the wide stopband feature of filters is enhanced.

Filter designs incorporating ferrite materials have been developed for the past 25 years. Usually a small polished single crystal of yttrium iron garnet (YIG) is placed in a microwave cavity which is operated at ferrimagnetic resonance [8]. Although the unloaded Q is very high, YIG filters can be used only in the low-power regime because of the narrow resonance line width of YIG. Spurious passbands always exist as a consequence of the higher order mode excitations of spin waves within the ferrite sphere, and spin wave instabilities can quickly build up as the microwave power increases. A wide-stopband filter could be constructed through an n-stub transmission line [9]. However, the stopband can extend three times the fundamental transmission frequency with sidelobes existing between the transmission peaks.

Typically, narrow-band filters imply low power operation and a limited range of stopband applications. We have developed a novel scheme by which narrow-band filters can operate at higher power level (compared with a resonant device) and over a wider range of frequencies (more than four times the fundamental mode of operation). Our design incorporates asymmetric stripline Y-junction circulators. As a ferrite circulator is generally used for microwave signal circulation purposes under a wide-band operation requirement, it acquires a cyclic symmetry of the ports and demands a deliberate match of the port impedances. As long as narrow-band transmission is considered, we might relax the cyclic symmetry of the ports to allow one more degree of freedom in designing a real circulator filter. Since maximum transmission occurs for frequencies above or below ferromagnetic resonance, the filter can operate at higher power levels than those operated at resonance, provided that the same ferrite material is used in the design. As long as the device can provide wide stopband attenuation, it represents one more example in which ferrites are utilized to protect electronic components in a high-power and/or high-noise environment.

A symmetrical circulator requires all the port separation angles to be equal (120°). For an asymmetrical circulator the cyclic threefold symmetry is no longer retained. However, twofold symmetry still applies and the dipole excitation can exist in the ferrite disk to meet the circulation conditions. Under circulation conditions the transmission coefficient becomes unity (in the low-loss limit) while the isolation and the reflection coefficients remain zero. In this theoretical treatment we adopt the Green's function approach [1], [2] to calculate the scattering matrix elements for an asymmetrical stripline Y-junction circulator. In Section II we develop a formula for the circulation conditions of an asymmetrical circulator. This complex equation yields, for given values of $4\pi M_s$, biasing field strength, and the desired circulation frequency ω_r, a value for the radius of the ferrite disk, R, and the ratio of the dielectric constant of the dielectric

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H. How and C. Vittoria are with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115.

C. Carosella is with the Office of Naval Research, Naval Research Laboratory, 4555 Overlook Ave. S.W., Washington, DC 20375.

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material filling the stripline to that of the ferrite disc, ϵ_d/ϵ_f. Strictly speaking, the above asymmetrical design cannot be referred to as a circulator design, because circulation conditions cannot always be achieved for an arbitrary input port. In our design only one port can be designated as the input port for circulation condition. Thus, on a restricted basis we call our device a circulator design.

In Section III the transmission characteristics associated with asymmetrical circulators under a wide frequency range of operation are discussed. Since we require band-stop capability for frequencies well above the circulation frequency (fundamental transmission mode), higher order terms need to be considered. Since the multipole series expansions converge extremely slowly, a repeated averaging scheme of the partial sums [10] has been used to accelerate the convergence. For frequency equal to five times the circulation frequency, more than 300 terms must be retained in the series expansions in order to achieve an accuracy of six digits. Although many filter designs incorporating a single asymmetrical circulator can produce a main transmission peak accompanied by sidelobes of reduced amplitudes, all of them require small values of the dielectric constant ratio, which are proved to be too small to be practical. On the other hand we found that, when two practical asymmetrical circulators are used in cascade, it is possible to obtain an overall transmission which does provide a single narrow transmission band with stopband extending many times its peak frequency.

II. Calculation

The stripline Y-junction ferrite circulator consists of two ferrite disks filling the space between a metallic center disk and two conducting ground plates [1]. The static magnetic field is applied parallel to the axis of the ferrite disks. We assume that the striplines propagate in TEM modes only and that the fields have no variation along the applied field direction. The electric as well as the magnetic field intensities on either side of the center conductor are equal and oppositely directed at any instant. Hence, the field problem needs to be solved for only one disk in association with the fields on the appropriate side of the inner conductors of the striplines. Fig. 1 depicts the geometry of such a stripline Y-junction circulator, outlining the central ferrite disk adjoined by three stripline ports. The angle θ denotes half the asymmetrical port separation angle (not necessarily equal to 60°), and ψ is half the suspension angle of the three ports. For such a noncyclic arrangement of the ports, exact circulation conditions can be achieved and under dipole excitation the field has the profile shown in Fig. 2.

Considering only the case of transverse electric (TE) waves, the electric field within the ferrite disk has only the z component, E_z. Bosma's Green's function approach [1] gives the electric field intensity $E_z(R,\phi')$ at the periphery of the ferrite disk and at the angle $\phi=\phi'$ that is generated by a unit source $H_\phi=\delta(\phi-\phi'')$ located at the edge of the disk. This Green's function takes the form

$$G(\phi';\phi'')=\frac{Z_{\text{eff}}}{\pi}\left\{\frac{-iJ_0(x)}{2J_0'(x)}+\sum_{n=1}^{\infty}J_n(x)\frac{P_n(x;\phi',\phi'')-iQ_n(x,\phi',\phi'')}{R_n(x;\phi',\phi'')}\right\} \quad (1)$$

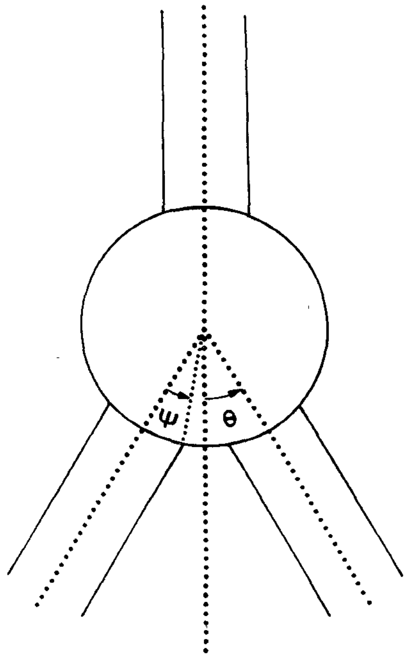

Fig. 1. Geometry of an asymmetrical circulator.

where

$$P_n=\frac{\kappa}{\mu}\frac{nJ_n(x)}{x}\sin n(\phi'-\phi'')$$

$$Q_n=J_n'(x)\cos n(\phi'-\phi'')$$

$$R_n=[J_n'(x)]^2-\left[\frac{\kappa}{\mu}\frac{nJ_n(x)}{x}\right]^2$$

$$\mu_{\text{eff}}=(\mu^2-\kappa^2)/\mu$$

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

$$x=kR$$

$$Z_{\text{eff}}=(\mu_0\mu_{\text{eff}}/\epsilon_0\epsilon_f)^{1/2}.$$

Here μ and κ are Polder tensor elements of the ferrite, μ_{eff} is the effective permeability of the ferrite, Z_{eff} is the intrinsic wave impedance, ϵ_f is the relative dielectric constant, R is the radius of the ferrite disk, k is the radial wave propagation constant, and $J_n(x)$ and $J_n'(x)$ are the Bessel function of the first kind with order n and the derivative of $J_n(x)$ with respect to x, respectively. Note that the Green function expression of (1) is unitary only if the ferrite is considered lossless, i.e., $G(\phi';\phi'')=-G^*(\phi'';\phi')$ when x is real.

As shown in Fig. 2, we denote the input port as port 1, the output port as port 2, and the isolation port as port 3. The port separation angles between ports 1 and 2, 2 and 3, and 3 and 1 are, respectively, 2θ, $\pi-\theta$, and $\pi-\theta$. The boundary

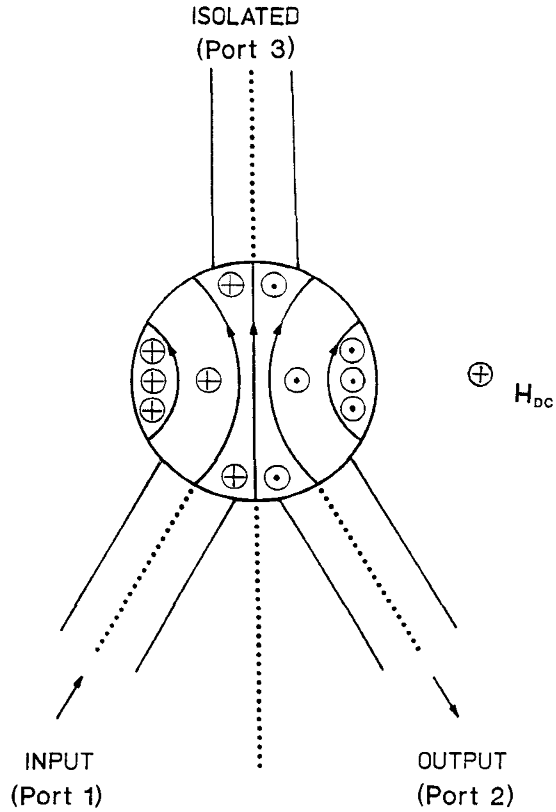

Fig. 2. Dipole excitation under circulation conditions.

conditions require that the magnetic field in the azimuthal direction be continuous across the edge of the disk. Hence, we write

$$H_\phi(R,\phi) = a_i \quad \text{for } \phi_i - \psi < \phi < \phi_i + \psi \text{ and } i = 1,2,3$$
$$= 0 \quad \text{elsewhere.} \tag{2}$$

Here the ϕ_i's are defined as $-\theta$, θ, and π for $i = 1$, 2, and 3, respectively. We define the average electric field intensity in the z direction at port i as A_i. Using the Green's function representation (eq. (1)), A_i can be put in the form

$$A_i = \sum_{j=1}^{3} G_{ij} a_j \tag{3}$$

with the interport impedance G_{ij} being defined by

$$G_{ij} = \frac{1}{2\psi} \int_{\phi_i - \psi}^{\phi_i + \psi} d\phi' \cdot \int_{\phi_j - \psi}^{\phi_j + \psi} d\phi'' G(\phi';\phi''). \tag{4}$$

Assume that the output and the isolated ports are terminated with reflectionless loads such that the so-called matching conditions hold at these ports. This can be done with stub tuners or some other temporary means, as is usually required for the output and isolation ports under isolation and insertion loss measurements of a regular (symmetrical) circulator [11]. This implies

$$\frac{A_2}{a_2} = \frac{A_3}{a_3} = -Z_d = -\frac{A_{in}}{a_{in}} \tag{5}$$

where $Z_d = 120\pi/(\epsilon_d)^{1/2}$ Ω is the wave impedance of the surrounding filling medium possessing a relative dielectric constant ϵ_d, and A_{in} and a_{in} denote the (average) electric and magnetic fields of the incoming waves at the input port. We may relate the surface field amplitudes at each port to the incident wave amplitudes (A_{in} and a_{in}) by introducing the well-known scattering matrix elements S_{11}, S_{21}, and S_{31} as

$$A_1 = (1 + S_{11}) A_{in} \tag{6a}$$

$$a_1 = (1 - S_{11}) a_{in} \tag{6b}$$

$$A_2 = S_{21} A_{in} \tag{6c}$$

$$A_3 = S_{31} A_{in}. \tag{6d}$$

In this paper we are mainly concerned with the design of a circulator filter where port 1 is purposely treated as the input port. The other six matrix elements do not enter into (6a) to (6d) and are of no concern to our filter design. They will not be discussed in this paper. $|S_{11}|^2$, $|S_{21}|^2$, and $|S_{31}|^2$ represent reflection, transmission, and isolation coefficients, respectively, and

$$|S_{11}|^2 + |S_{21}|^2 + |S_{31}|^2 = 1$$

if the ferrite is lossless, i.e., the scattering matrix (S_{ij}) is unitary.

The purpose of the following analysis is to relate S_{11}, S_{21}, and S_{31} to G_{ij}. After elimination of the A_i's in (2) to (6), one obtains the following:

$$G'_{11}a'_1 + G'_{12}a'_2 + G'_{13}a'_3 = 2 \tag{7a}$$

$$G'_{21}a'_1 + G'_{22}a'_2 + G'_{23}a'_3 = 0 \tag{7b}$$

$$G'_{31}a'_1 + G'_{32}a'_2 + G'_{33}a'_3 = 0 \tag{7c}$$

$$S_{11} = 1 - a'_1 \tag{7d}$$

$$S_{21} = -a'_2 \tag{7e}$$

$$S_{31} = -a'_3 \tag{7f}$$

where the normalized quantities G'_{ij} and a'_i are defined by

$$G'_{ij} = \delta_{ij} + \frac{G_{ij}}{Z_d} \tag{8a}$$

$$a'_i = \frac{a_i Z_d}{A_{in}}. \tag{8b}$$

Therefore, via (7a) to (7c), the (a'_i)'s can be solved in terms of the (G'_{ij})'s. This solves S_{11}, S_{21}, and S_{31} via (7d) to (7f). We introduce the following notation in order to simplify the expressions of S_{11}, S_{21}, and S_{31}:

$$Z=\frac{1}{\pi}\frac{Z_{\mathrm{eff}}}{Z_d}$$

$$A=\frac{\psi J_0(x)}{J_0'(x)}$$

$$B_n=J_n'(x)\frac{2\sin^2 n\psi}{n^2\psi}$$

$$C_n=\frac{\kappa}{\mu}\frac{n}{x}J_n(x)\frac{2\sin^2 n\psi}{n^2\psi}$$

$$D_n=\frac{J_n(x)}{[J_n'(x)]^2-\left[\frac{\kappa}{\mu}\frac{nJ_n(x)}{x}\right]^2}$$

$$a=Z\cdot\left\{A+\sum_{n=1}^{\infty}\left[(-1)^n B_n D_n\cos n\alpha\right]\right\}$$

$$b=Z\cdot\left\{-\sum_{n=1}^{\infty}\left[(-1)^n C_n D_n\sin n\alpha\right]\right\}$$

$$c=Z\cdot\left[A+\sum_{n=1}^{\infty}(B_n D_n\cos 2n\alpha)\right]$$

$$d=Z\cdot\sum_{n=1}^{\infty}(C_n D_n\sin 2n\alpha)$$

$$g=Z\cdot\left[A+\sum_{n=1}^{\infty}(B_n D_n)\right]$$

$$\Theta=G_{11}'=G_{22}'=G_{33}'=1-ig$$

$$\Phi_1=G_{12}'=-G_{21}'^{*}=-d-ic$$

$$\Phi_2=G_{23}'=G_{31}'=-G_{32}'^{*}=-G_{13}'^{*}=-b-ia$$

$$\begin{aligned}\Delta&=\det|G_{ij}'|\\&=\Phi_1\Phi_2^2-\Phi_1^*\Phi_2^{*2}+\Theta(\Theta^2+\Phi_1\Phi_1^*+2\Phi_2\Phi_2^*)\\&=(1-3g^2+2a^2+2b^2+c^2+d^2)\\&\quad+i[-g(3-g^2+2a^2+2b^2+c^2+d^2)-4abd-2(b^2-a^2)c].\end{aligned}$$

The scattering matrix elements S_{11}, S_{21}, and S_{31} can be finally written as

$$\begin{aligned}S_{11}&=1-2\Delta^{-1}(\Theta^2+\Phi_2\Phi_2^*)\\&=1+\Delta^{-1}[(-2+2g^2-2a^2-2b^2)+4ig)]\end{aligned}\quad(9a)$$

$$\begin{aligned}S_{21}&=-2\Delta^{-1}(\Phi_2^2+\Phi_1^*\Theta)\\&=-2\Delta^{-1}[(-a^2+b^2+cg-d)\\&\quad+i(2ab+db+c)]\end{aligned}\quad(9b)$$

$$\begin{aligned}S_{31}&=-2\Delta^{-1}(\Phi_1^*\Phi_2^*-\Theta\Phi_2)\\&=-2\Delta^{-1}[(bd+ag-ac+b)\\&\quad+i(a-bc-ad-bg)].\end{aligned}\quad(9c)$$

The input impedance at port 1 is

$$Z_{\mathrm{in}}=A_1/a_1=\left(-1+\frac{\Delta}{\Theta^2+\Phi_2\Phi_2^*}\right)Z_d.\quad(10)$$

Circulation conditions are obtained by setting S_{31} to zero. This implies, from (9c), that

$$\Theta=\frac{\Phi_1^*\Phi_2^*}{\Phi_2}.\quad(11)$$

Using (11) and the equality

$$\Theta+\Theta^*=(\Phi_1\Phi_2^2+\Phi_1^*\Phi_2^{*2})/(\Phi_1\Phi_2^*)=2\quad(12a)$$

Δ can be written as

$$\Delta=\Phi_2^{-3}(\Phi_2^3+\Phi_1^{*2}\Phi_2^*)(\Phi_1\Phi_2^2+\Phi_1^*\Phi_2^{*2}).\quad(12b)$$

Substituting (12a) and (12b) into (9a), (9b), and (10), one obtains

$$S_{11}=0\quad(12c)$$

$$S_{21}=-\Phi_2/\Phi_2^*\quad(12d)$$

$$Z_{\mathrm{in}}=Z_d.\quad(12e)$$

Note that (12a), and hence (12b) to (12e), are obtained only if the parameter g is real, i.e., the ferrite material is lossless. Therefore, for lossless material under exact circulation conditions, the transmission coefficient is unity, the reflection and the isolation coefficients are reduced to zero, and the input impedance is equal to the wave impedance of the surrounding dielectric medium filling the stripline ports. Note that for the symmetrical case $\alpha=60°$ this implies $a=c$, $b=d$, $\Phi_1=\Phi_2$, and the above equations, (11) and (12c) to (12e), are identical to those obtained in [4], where only lossless ferrite material is considered. For the lossless case it is most convenient to rewrite the complex circulation equation, (eq. (11)), in two real equations:

$$c^2+d^2-g^2=1\quad(13a)$$

$$a^2(1-d)+b^2(1+d)-2abc=0.\quad(13b)$$

For given values of $4\pi M_s$, desired circulation frequency ω_f, port separation angle 2θ, and port suspension angle 2ψ, (13a) and (13b) determine the possible values of the ferrite disk radius R and the dielectric constant ratio ϵ_d/ϵ_f, since a circulator is normally biased at off-resonant conditions.

III. Results

In order to account for the resonant behavior of the ferrite, complex Polder tensor elements are used:

$$\mu=1+\frac{\omega_m(\omega_0+i\Delta\omega)}{(\omega_0+i\Delta\omega)^2-\omega^2}\quad(14a)$$

$$\kappa=\frac{\omega_m\omega}{(\omega_0+i\Delta\omega)^2-\omega^2}.\quad(14b)$$

Here

$$\omega_m=4\pi\gamma M_s$$

$$\omega_0=\gamma H_{\mathrm{int}}$$

$$\Delta\omega=\gamma\Delta H$$

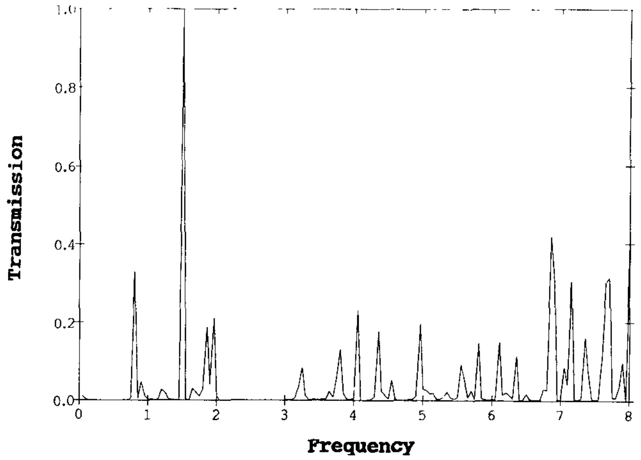

Fig. 3. Transmission characteristics of an asymmetrical circulator: $\psi = 10^0$, $\theta = 15^0$, $\omega_0 = 2$, $\omega_f = 1.5$, $\Delta H = 0.012$.

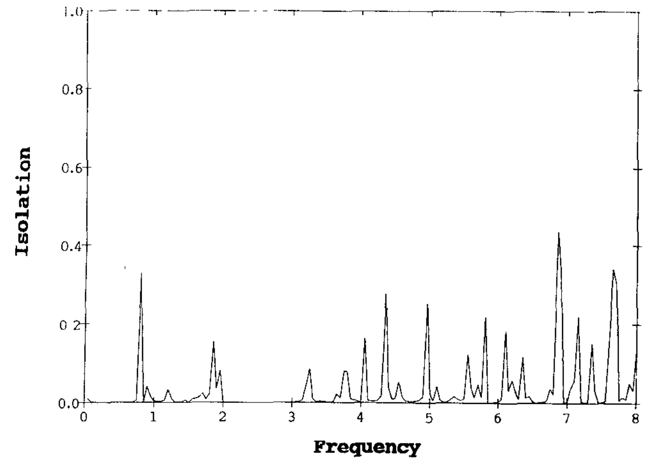

Fig. 4. Isolation characteristics of the circulator associated with Fig. 3.

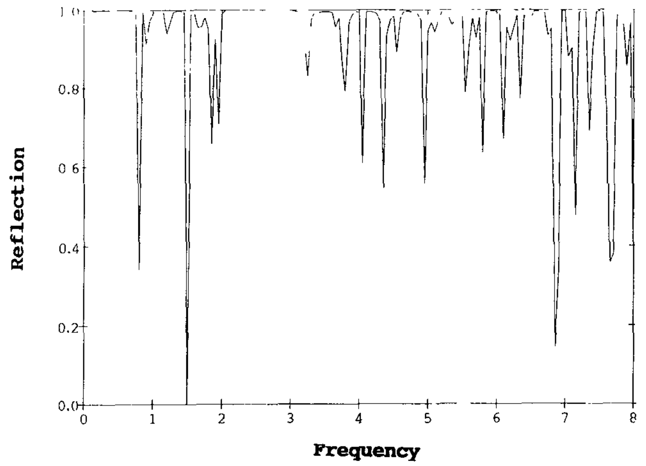

Fig. 5. Reflection characteristics of the circulator associated with Fig. 3.

with γ, H_{int}, $4\pi M_s$, and ΔH being the gyromagnetic ratio, the static internal magnetic field in the ferrite disk, the saturation magnetization, and the resonance line width of the ferrite material, respectively. In this analysis we normalize the fields with respect to $4\pi M_s$ and the angular frequencies with respect to $4\pi\gamma M_s$. ΔH is taken to be 0.012 (in units of $4\pi M_s$). This corresponds to $\Delta H = 50$ Oe for (polycrystaline) lithium ferrite, for example. The ΔH of typical ferrite materials ranges from 50 to 500 Oe. As is well known, the imaginary components of μ and κ are important only when the frequency ω approaches resonance frequency, which is close to ω_0. In this case dissipation occurs and the reflection coefficient reaches a value almost equal to unity while the transmission and isolation coefficients remain very small.

For a given circulation frequency ω_f, circulation equations (13a) and (13b) determine x and Z, which in turn specify the ferrite disk radius R and the dielectric constant ratio ϵ_d/ϵ_f:

$$R = x(\epsilon_f \mu_{\text{eff}})^{-1/2}(c/\omega_f) \tag{15a}$$

$$\epsilon_d/\epsilon_f = \mu_{\text{eff}}/(\pi^2 Z^2). \tag{15b}$$

Transmission, isolation, and reflection characteristics for other frequencies can be then plotted utilizing (9a) to (9c) with fixed values of R and ϵ_d/ϵ_f. For large values of the frequencies it is found that the expansion series defining the constants a, b, c, d, and g converge extremely slowly. Since the expansions involved behave more or less like the series $\Sigma(-1)^n(1/n)$ for large values of n, a repeated averaged scheme [10] of the partial sums has been exploited to accelerate the convergence. Even with this technique a calculation of the constant g for a frequency equal to five times the frequency $4\pi\gamma M_s$ requires more than 300 terms in the expansion to be retained in order to achieve an accuracy of six digits.

Figs. 3 to 5 show, respectively, the transmission, isolation, and reflection coefficients of an asymmetrical stripline circulator which is biased above resonance with $\psi = 10^0$, $\theta = 15^0$, $\omega_0 = 2$, and $\omega_f = 1.5$. For frequencies far off the resonance region the sum of these three coefficients yields a value close to unity, indicating that the expansions of the multiple terms have been calculated correctly. For lithium ferrite, $4\pi M_s$ equals 4100 G and the above circulator design requires the disk radius to be 2.05 mm. The exact circulation condition occurs at the desired frequency $\omega_f = 1.5$, where the transmission coefficient is close to unity and the isolation and reflection coefficients are roughly zero. Owing to higher order mode excitations of the ferrite disk, other transmission peaks with reduced amplitudes also appear in Fig. 3. The circulator with the above-mentioned characteristics requires a dielectric constant ratio ϵ_d/ϵ_f equal to 0.0016. For an ϵ_f value in the range of 12 to 14 this implies a ϵ_d value of 0.02, which is too small to be practical.

We have tried many plots with transmission characteristics similar to Fig. 3 in which a narrow transmission band is accompanied by other sidebands of reduced amplitudes. However, all of them require impractical ϵ_d/ϵ_f values. In order to develop circulator filters for which practical ratios of ϵ_d/ϵ_f may be incorporated in the design, we have considered a cascade structure design of the stripline circulators. Figs. 6 and 7 show the transmission characteristics of two asymmetrical circulators. Fig. 6 is associated with a circulator biased below resonance with $\psi = 30^0$, $\theta = 70^0$, $\omega_0 = 0$, and $\omega_f = 2$, and Fig. 7 is associated with a circulator biased above resonance with $\psi = 45^0$, $\theta = 45^0$, $\omega_0 = 2.1$, and $\omega_f = 2$. If lithium ferrite is used, for example, they require the disk radii to be 1.53 mm and 0.38 mm, respectively. The ϵ_d/ϵ_f

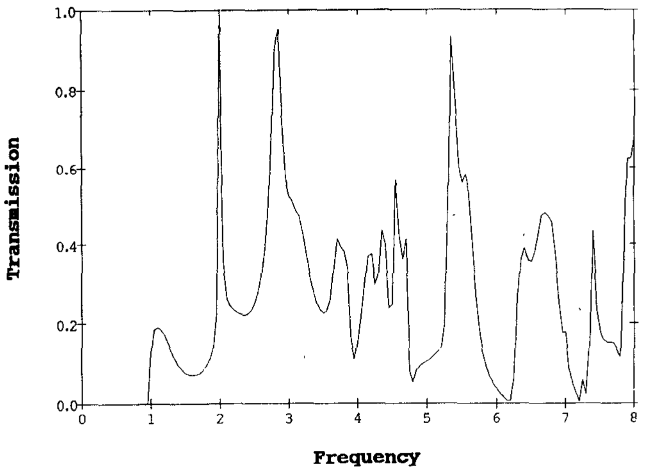

Fig. 6. Transmission characteristics of an asymmetrical circulator: $\psi = 30^0$, $\theta = 70^0$, $\omega_0 = 0$, $\omega_j = 2.0$, $\Delta H = 0.012$.

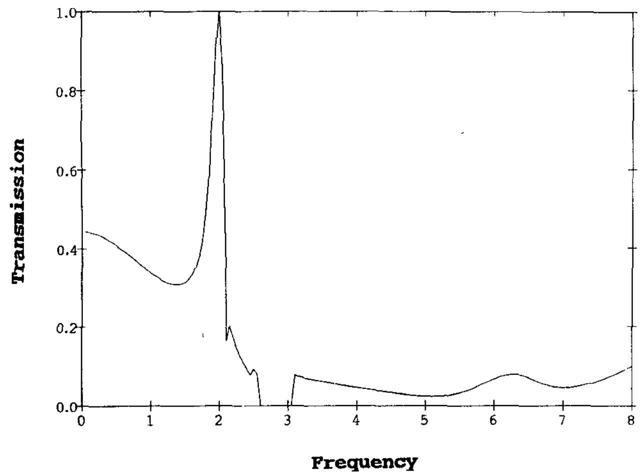

Fig. 7. Transmission characteristics of an asymmetrical circulator: $\psi = 45^0$, $\theta = 45^0$, $\omega_0 = 2.1$, $\omega_j = 2.0$, $\Delta H = 0.012$.

ratios are required to be 0.104 and 0.092, respectively, which implies $\epsilon_d \approx 1.1$ to 1.5. Fig. 6 is representative of most circulators where multipole excitations make the transmission possible at higher order frequencies, and the side lobes are almost as high as the main transmission peak. Figs. 6 and 7 do not show filter characteristics. However, when used in cascade, they yield the result of Fig. 8, which shows a narrow-band filter with the following characteristics: minimal insertion loss at transmission and attenuation of the order of 15 dB outside transmission. A transmission bandwidth of 0.067 at 3 dB points is calculated, and the stopband extends four times the fundamental transmission frequency. A cascade structure of circulators can be achieved without affecting each individual characteristic if isolators are inserted between two circulators. Most practical field-displacement isolators cover broad bandwidths (two octaves and wider) and have insertion losses smaller than 1 dB. When these isolators are used in a cascade structure, the total insertion loss will still be relatively low. Fig. 8 is obtained by multiplying S_{31} of the two devices associated with Figs. 6 and 7. In order to reduce interaction between the two devices it is suggested that a ferrite isolator be physically placed between the two circulator devices.

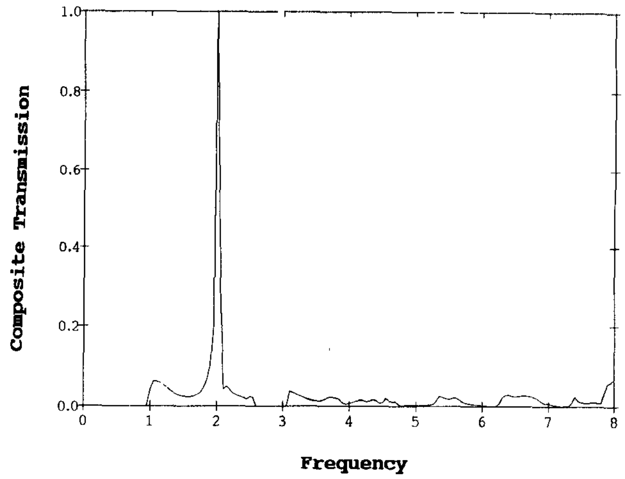

Fig. 8. Characteristics of the cascaded transmission associated with Fig. 6 and Fig. 7.

Note that the transmission peak in Fig. 7 is much wider than the corresponding one in Fig. 8. This causes little problem in aligning the two transmission peaks in a cascade structure where thermal shift might be a problem (although we can apply thermal compensation technique [11] to each individual circulator). If lithium ferrite is used for the devices of Figs. 6 and 7, the overall transmission, Fig. 8, filters out the desired signals at 23 GHz and blocks out all the unwanted signals up to a frequency equal to 92 GHz. Since maximum transmission occurs either well above or well below the ferrimagnetic resonance frequency, say nominally 0 GHz and 64 GHz for the above case, this device may be used at high power levels, say, several hundred watts of CW power handling capacity for a typical stripline circulator working at 30 GHz [11].

IV. Discussion

We have formulated a novel scheme of filter design incorporating asymmetrical stripline Y-junction circulators. When two asymmetrical circulators are used in cascade, a filter characterized by a narrow transmission band and a very wide stopband is obtained. Insertion loss at transmission frequency can be very low (< 1 dB), because the ferrites are biased away from the ferrimagnetic resonant frequency. Insertion loss at frequencies outside the transmission band is about two times lower than that of traditional ferrite filters. However, the stopband is much wider than in traditional filters. As higher order mode excitations always exist in traditional filters, they are effectively suppressed in the design incorporating asymmetrical stripline Y-junction circulators. These theoretical findings reveal that filter design incorporating circulators can be potentially useful for low- and high-microwave-power applications. Experimental work concerning asymmetrical stripline circulators will be published elsewhere.

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