The Ring-Network Circulator for Integrated Circuits: Theory and Experiments

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Abstract— **The theoretical model of a ring network junction circulator introduced in 1965 is reexamined and further elaborated, in view of its prospects for compatibility with accomplished and anticipated advances in microcircuit technology. Following a brief review of the theory, solutions are presented to illustrate the potential for novel, efficient designs with options including miniature, self-magnetized, reversible, broadband, superconducting, or other advantageous characteristics. New experimental models are showing good conformance to theoretical predictions for this promising alternative circulator design concept.**

I. Introduction

THE CONCEPT of a ring network circulator was introduced with a theoretical analysis in 1965 [1], [2] and was the subject of experimental investigation at that time [3]. The specific embodiment considered is a ring composed of three identical nonreciprocal phase shifters alternating with three identical symmetrical, reciprocal T junctions (see Fig. 1), constituting a three-port junction circulator. The dual objectives of the original study were: to consider the ring network in its own right as a potentially advantageous or alternative circulator design concept, but also to explore whether it might be developed into a useful model representing circulators of the resonant type [4], or indeed junction circulators in general.

The logic of the analysis was formulated to assure that no physically realizable lossless model of the network would escape consideration. As shown in Appendix II of [1] and summarized briefly below (Section II), a straightforward formulation of clockwise- and counterclockwise-propagating partial waves leads to a solution in the form of a characterisation of the differential phase shifters in terms of assumed physically realizable scattering parameters of the T junctions which together yield perfect circulation. Computations performed at the time for a range of examples showed that many did indeed exhibit ideal circulation as might have been expected; surprisingly, it was often found that the magnitudes of nonreciprocity required were unexpectedly small. This suggested a potential for circulator designs with highly efficient use of gyrotropic material.

At the time of those first publications, however, exploitation of the concepts of planar circuits, integration, and miniaturization was only just getting under way. Therefore the potential advantages of the ring network were not so apparent,

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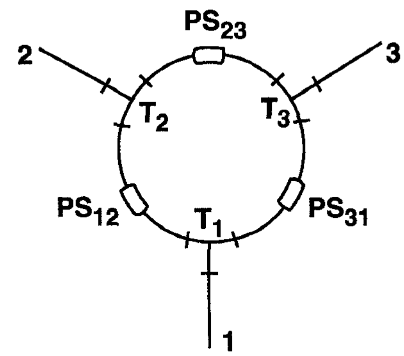

Fig. 1. Schematic diagram of the ring network. T and PS denote, respectively, symmetrical T junctions and nonreciprocal phase shifters.

as compared with the supposed disadvantages of loss and complexity suggested by those initial designs. Thus, the idea seems to have received only slight attention on the part of the microwave nonreciprocal device community. With dramatic advances in miniature microwave circuits in the interim, and with new developments now on the horizon such as thin deposited ferrite films including those made of hexagonal "self-magnetized" materials (magnetoplumbites), miniature composite ferrite-semiconductor substrates, and possibly also low-loss high-temperature superconducting planar circuits [5], a new look into the virtues and features of the ring network circulator is warranted.

In this present cycle of investigation we show that the theory leads to solutions representing a very wide range of circulator designs, and we show how it furnishes information on frequency dependence, specifically on bandwidth, and on the influence of dissipative loss. These new results show significant potential for very broad bandwidth and highly efficient use of gyrotropic materials in compact planar designs with favorable structure for many useful modes of operation including reversible and permanently self-magnetized versions.

II. Basic Analysis

The general three-port transmission-line junction can be characterized by a 3×3-dimensional scattering matrix with nine complex elements: thus, 18 real parameters. The constraints of geometrical symmetry and reciprocity reduce this number to four in the case of a T junction (two-fold symmetry)

$$S_T = \begin{bmatrix} r & s & s_d \\ s & r & s_d \\ s_d & s_d & r_d \end{bmatrix}. \quad (1)$$

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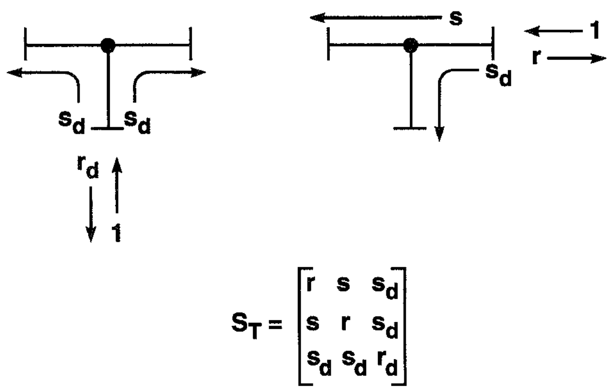


Fig. 2. Definitions of the scattering coefficients of the symmetrical T junction.

The scattering coefficients are represented in the diagram, Fig. 2. As shown in Appendix I of [1], the further constraint of energy conservation results in the class of all lossless, symmetrical, reciprocal T junctions being encompassed by four real parameters; we adopt $\sigma_{a,b,c}$ and γ: the (real) phase angles, or arguments, of three complex numbers of unit magnitude plus one additional real angle. Defining $s_a = e^{j\sigma_a}$, etc., where $j = \sqrt{-1}$, we have

$$\left.\begin{aligned} r &= \tfrac{1}{2}(s_a + s_b\cos^2\gamma + s_c\sin^2\gamma) \\ s &= \tfrac{1}{2}(-s_a + s_b\cos^2\gamma + s_c\sin^2\gamma) \\ r_d &= s_b\sin^2\gamma + s_c\cos^2\gamma \\ s_d &= \tfrac{1}{\sqrt{2}}(s_b - s_c)\cos\gamma\sin\gamma \end{aligned}\right\} \tag{2}$$

with $|s_a| = |s_b| = |s_c| = 1$.

It is useful to note that, from the first two of (2)

$$r - s = s_a; \quad \text{thus } |r - s| = 1.$$

Each assignment of values to the four parameters within their respective finite ranges yields an unique prescription for a suitable T junction with four complex scattering coefficients r_d, s_d, r, s which forms the basis of an individual circulator design, and conversely.

The simplifying assumption of Y symmetry (i.e., three-fold symmetry, which is to be applied in Section IV) leads to some interesting and useful conditions on the scattering coefficients. In (2) for S_T in terms of the four real parameters γ and $\sigma_{a,b,c}$, setting $r_d = r$ and $s_d = s$ leads to $\tan 2\gamma = 2\sqrt{2}$, hence

$$\begin{aligned} &\text{either} \quad \gamma = 35.26^\circ \quad \text{with} \quad s_a = s_c \\ &\text{or} \quad \gamma = -54.74^\circ \quad \text{with} \quad s_a = s_b. \end{aligned}$$

Also, in the special case of Y symmetry, unitarity of the scattering matrix S (a manifestation of energy conservation, namely $S^\dagger S = I$, where † denotes the Hermitean adjoint and I is the unit matrix) leads to

$$|r|^2 + 2|s|^2 = 1 \quad \text{and} \quad \cos(\rho - \sigma) = -\frac{|s|}{2|r|}$$

where ρ, σ are, respectively, the phase angles of r and s.

The nonreciprocal phase shifters (assumed matched) are characterized by two parameters; namely, the mean phase factor $\epsilon = \exp[-j(\phi_+ + \phi_-)/2]$, and the (half-)differential phase factor $\delta = \exp[-j(\phi_+ - \phi_-)/2]$, where ϕ_+, ϕ_- are the respective phases for the clockwise and counterclockwise senses of propagation through a single sector of the ring. Imposition of the circulation condition, namely unit input at port 1 and isolation of port 3 (see Fig. 1), leads to an algebraic equation for ϵ^2 and a formula for δ^3 in terms of ϵ. In both of these relations, the coefficients are functions of the "internal" scattering coefficients r and s of the T junctions. First, we define

$$\left.\begin{aligned} a_4 &= (r - s)^3(r + s) \\ a_3 &= -s(r - s)^2 \\ a_2 &= -2r(r - s) \\ a_1 &= s \\ a_0 &= 1 \end{aligned}\right\}. \tag{3}$$

Now ϵ is a solution of

$$A_8\epsilon^8 + A_6\epsilon^6 + A_4\epsilon^4 + A_2\epsilon^2 + A_0 = 0 \tag{4}$$

where

$$\left.\begin{aligned} A_8 &= A_0^* = a_4 a_0^* \\ A_6 &= A_2^* = a_4 a_2^* + a_2 a_0^* - a_3 a_1^* \\ A_4 &= |a_4|^2 + |a_2|^2 + |a_0|^2 - |a_3|^2 - |a_1|^2 \end{aligned}\right\}. \tag{5}$$

Then, in terms of ϵ, the corresponding value of δ is given by

$$\delta^3 = \frac{a_4\epsilon^4 + a_2\epsilon^2 + a_0}{a_3\epsilon^3 + a_1\epsilon}. \tag{6}$$

For the assumed ideal of perfect circulation, solutions are subject to the conditions

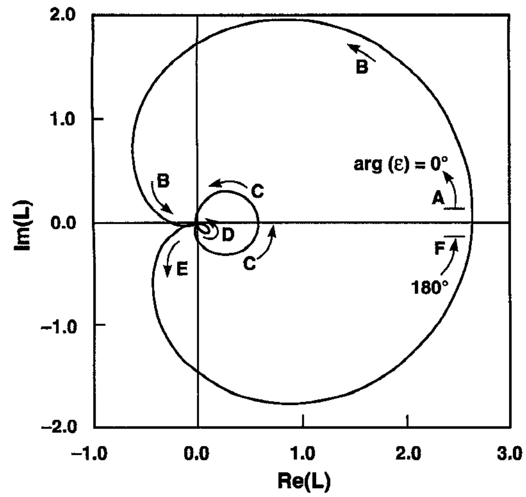
$$|\epsilon| = 1, \quad |\delta| = 1. \tag{7}$$

We note some useful symmetries in these basic relations: for a given solution ϵ, (4) is also satisfied by $-\epsilon$, and under such a phase change of $\arg(\epsilon)$ by $\pm\pi$ the sign of δ^3 is reversed. Taking the cube root, we have that for a given solution δ, (6) is also satisfied with $\arg(\delta) \pm 2\pi/3$. The most significant consequence is that solutions can always be transformed so as to bring the required magnitude of $\arg(\delta)$ to $\pi/6$ (i.e., 30°) or less, which is important for practical device design as well as for circulator theory in general.

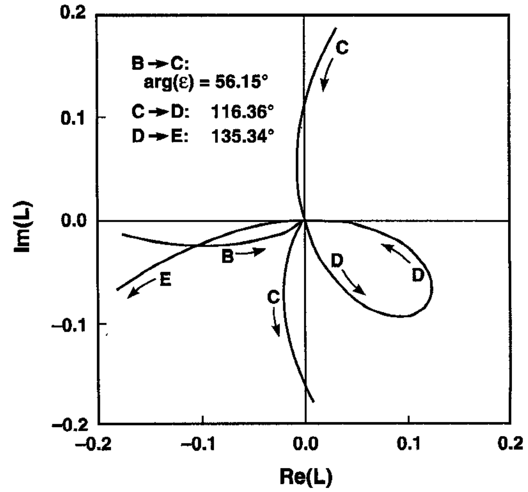
III. Further Analysis and Illustrations

The result of the analysis sketched in Section II is in the nature of an "existence proof"; it imposes no limitation, and conversely provides no guidance, as to how the phase and reflection characteristics of the components are to be physically realized. Frequency dependence does not appear explicitly, but is implied by the dispersive properties of the components. Ideal absence of dissipation is assumed in the part of the analysis leading to prescriptions for perfect circulation, but the influences of loss can be fully investigated within the formulation. For a simple estimate, the conditions of (7) can be lifted so as to represent dissipative loss in the phase shifters by making $|\epsilon|$ and $|\delta|$ less than unity; an example will be presented in Section IV.

Let $L(\epsilon)$ denote the left-hand side of (4). We seek solutions of $L(\epsilon) = 0$. The behavior of the function $L(\epsilon)$ is complicated and sensitive to the values of r and s. A particular case is



(a)



(b)

Fig. 3. (a) Illustrating the variation of the left-hand side $L(\epsilon)$ of (4), $L(\epsilon) = 0$, on the complex plane as the phase angle $\arg(\epsilon)$ of the unknown complex phase factor varies from 0 to 180°. The parameters for this case are given in the text. (b) Enlarged view of the part of the variation of $L(\epsilon)$ near the origin of the complex plane in the example of Fig. 3(a), showing the four roots of (4) listed in Table I.

illustrated in Fig. 3(a) as $\arg(\epsilon)$ varies from zero to 180°. The parameters η and ζ (defined in Section IV) which specify the T junctions for this example are listed in Table I, below. The itinerary of $L(\epsilon)$ on the complex plane from A [$\arg(\epsilon) = 0°$] to F [180°] is indicated in the figure. Four zeros of the function are pictured in the enlarged view, Fig. 3(b), and the values of ϵ and δ for this set of solutions are listed in Table I. On the basis of (7), only the latter two of the four solutions are retained as leading to physically meaningful values of δ. The first two constitute an unphysical double root for which δ (6) is indeterminate.

In this example, Solution 4 calls for $\arg(\delta)$ which is less than 30°. We shall see in further examples that circulation can occur with even much smaller values of this parameter; in fact, the model actually imposes no lower limit on the magnitude of nonreciprocal differential phase (except, of course, that

TABLE I

$\eta = 0.8$, $\zeta = 0.533$		
Solution No.	ϵ	δ
1,2	$1.0\angle 56.15°$	$-\angle -$
3	$1.0\angle 116.36°$	$1.0\angle 39.93°$
4	$1.0\angle 135.34°$	$1.0\angle 26.40°$

$\arg(\delta) = 0$ is excluded). This is an important characteristic of the ring network and means that it admits circulators embodying small amounts of gyrotropic matter, suggesting designs with small size and low magnetic loss.

We note that this result may appear to contradict a general theorem of Carlin [6]. The theorem is based on a circuit model of a circulator in which nonreciprocity is embodied in a "gyrator" (Tellegen [7]), a circuit element characterized by $\phi_+ = 180°$, $\phi_- = 0°$ [equivalent to our $\arg(\epsilon) = \arg(\delta) = 90°$]. It states that the minimum number of gyrators required for circulation is one, which may seem to set a lower limit on $|\arg(\delta)|$ of $90/3 = 30°$. It is a feature of the ring network, however, that it is not formulated in terms of gyrator units. Rather, nonreciprocity is represented by the parameter δ whose phase is a continuous variable. Thus, the ring-network model may be considered to offer greater generality, and there is no incompatibility between its predictions of small $|\arg(\delta)|$ and those of Carlin's circulator theorem.

To model frequency dependence, we require knowledge of the dispersive properties of the components. Of course success in physical realization of the ring network circulator depends on the designer's skill in making reciprocal T junctions and nonreciprocal phase shifters which conform to the prescribed values of scattering coefficients and possess favorable dispersive properties. Information must be developed on phase and reflection behavior of "intentionally mismatched" T junctions (to borrow the patent terminology [2]) which is not generally available, although collections of useful related formulas and data have been presented in the microwave literature [8].

In Section IV we consider a specific example of T junction design and its consequences for the resulting circulator.

IV. Reactive Loading of the T Junction

We illustrate how the design of a T junction with prescribed scattering characteristics can be accomplished, how these parameters are interrelated under the requirements of reciprocity, energy conservation, and geometrical symmetry, and how they in turn determine the values of the nonreciprocal phase-shifter parameters ϵ and δ required for circulation. We also show how, with reasonable assumptions as to the dispersive properties of the components, the predicted frequency-dependence of circulator performance can be evaluated.

In the present example we assume the T to be symmetrically loaded by a shunt capacitor and series inductors. The effects can be formulated analytically in the special case of a junction possessing three-fold rotational symmetry (i.e., a Y junction: $r_d = r$, $s_d = s$) loaded by a shunt capacitor C at the junction and by series inductors L connected from the junction to each of the three ports (Fig. 4). We can investigate bandwidth properties of this model through the linear frequency-dependences of capacitive susceptance and inductive reactance, together

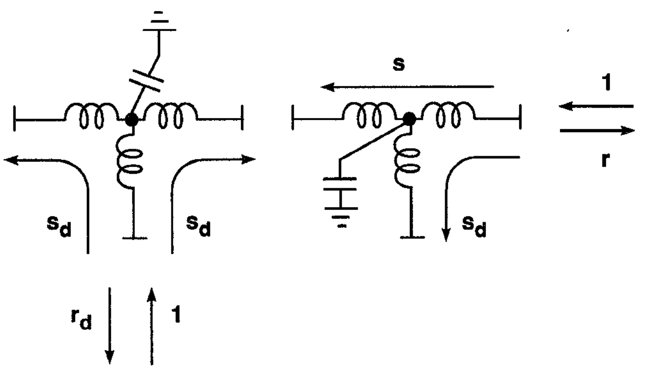


Fig. 4. Schematic diagram of a symmetrical junction loaded with shunt capacitance and series inductances. The junction has the electrical symmetry of a three-fold symmetrical Y.

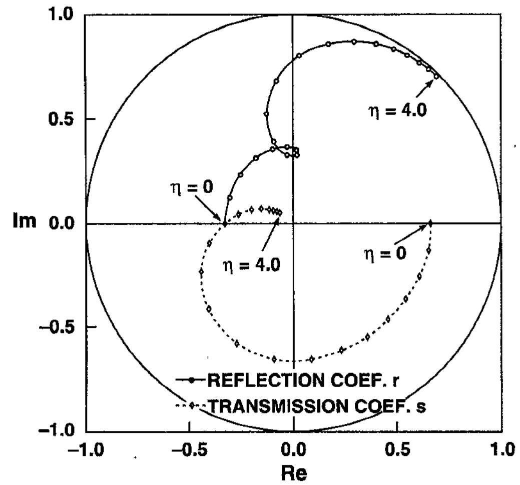


Fig. 5. Representation on the complex plane of scattering coefficients r and s of a Y junction as the capacitive susceptance parameter η is varied from 0 to 4. The inductive reactance parameter ζ is given by $\zeta/\eta = 2/3$.

with appropriate assumptions about dispersion in the phase shifters.

Let $\omega CZ_0 = \eta$ and $\omega LY_0 = \zeta$, where ω is the radian frequency and $Z_0 = 1/Y_0$ is the characteristic impedance of the lines connected to the three ports. Straightforward analysis of voltage and current relations at the input and output ports of the Y junction of Fig. 4 leads to the following expressions for r and s.

$$\left.\begin{aligned} r &= \frac{-1 + j[-\eta + \zeta(3 - \eta\zeta)]}{3 - 2\eta\zeta + j[\eta + \zeta(3 - \eta\zeta)]} \\ s &= \frac{2}{3 - 2\eta\zeta + j[\eta + \zeta(3 - \eta\zeta)]} \end{aligned}\right\}. \tag{8}$$

In the special cases $\zeta = 0$ (capacitive loading only) or $\eta = 0$ (inductive loading only), (8) reduce to

$$\left.\begin{aligned} r &= -\frac{1+j\eta}{3+j\eta} \\ s &= \frac{2}{3+j\eta} \end{aligned}\right\} \tag{9}$$

or

$$\left.\begin{aligned} r &= \frac{-1+3j\zeta}{3(1+j\zeta)} \\ s &= \frac{2}{3(1+j\zeta)} \end{aligned}\right\} \tag{10}$$

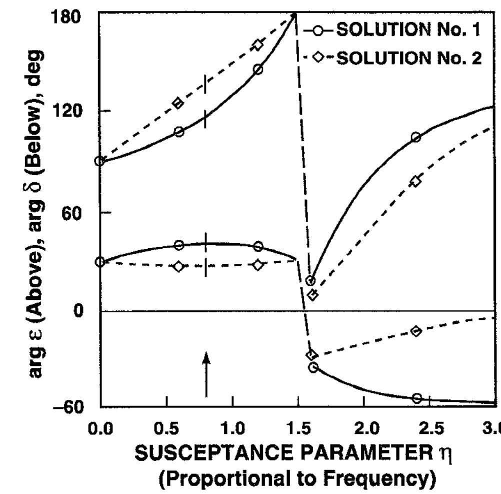


Fig. 6. Solutions of (4). Average phase $\arg(\epsilon)$ and (half-) differential phase $\arg(\delta)$ as functions of the capacitive susceptance parameter η, with $\zeta/\eta = 2/3$.

respectively. When not loaded, the Y is characterized by the real values $r = -1/3$, $s = 2/3$; with increase in loading these eventually go to total reflection with $r = -1$, $s = 0$ in the capacitive, and $r = +1$, $s = 0$ in the inductive case. When both capacitance and inductance are incorporated, performance of the Y is complicated, as expected; an example in which we have assigned the ratio $\zeta/\eta = 2/3$ for the inductive and capacitive loading, and with η varying from zero to four, is shown in Fig. 5. This behavior permits an interesting view of its influence on the ring network circulator characteristics.

The courses of $\arg(\epsilon)$ and $\arg(\delta)$ for two acceptable solutions of (4) and (6) satisfying the conditions of (7) as functions of η, with $\zeta/\eta = 2/3$, are shown in Fig. 6. We now select a range of Solution 2 in the interval $1.8 < \eta < 3.0$ for our illustration because it exemplifies the capability for circulation with small amounts of differential phase. (In Fig. 6, note that in that interval $\arg(\delta)$ varies from $-25.1°$ to $-6.1°$. The corresponding $\arg(\epsilon)$ varies from $25.2°$ to $108.4°$). Each set of associated parameters yields ideal circulation, i.e., zero insertion loss and very high isolation and return loss over the band: beyond 60 dB (not infinite, due only to imprecision from computational round-off).

Since η, ζ are proportional to frequency, this performance is comparable to the type of frequency-dependence characterizations to which circulator designers are accustomed. Thus, in this example the "bandwidth" is *unlimited* (the only limits are those of our arbitrary choice of range of attention: about ±25% in this example). Such an ideal is achievable, or approachable, if the dissipative losses of the T junctions and phase shifters are reasonably low and if their dispersive characteristics conform reasonably well to the phase and amplitude relations prescribed by the theory. To illustrate this conclusion in a simple but realistic manner, we consider the following examples.

First, we incorporate a small dissipative loss in the propagation constants of the phase shifters ($|\epsilon| = |\delta| = 0.998$), leading to a minimum insertion loss of about 0.2 dB. The result is correspondingly degraded isolation (now ranging from 56 to

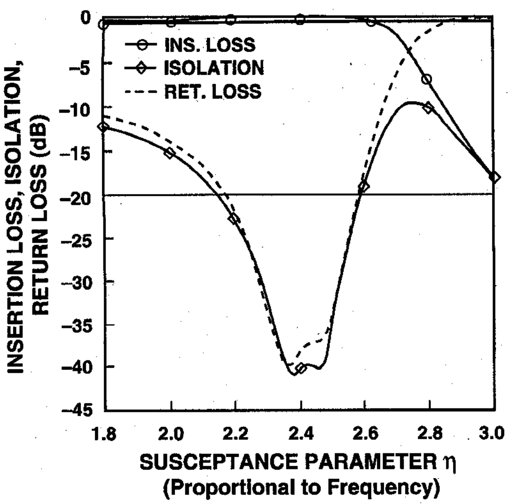


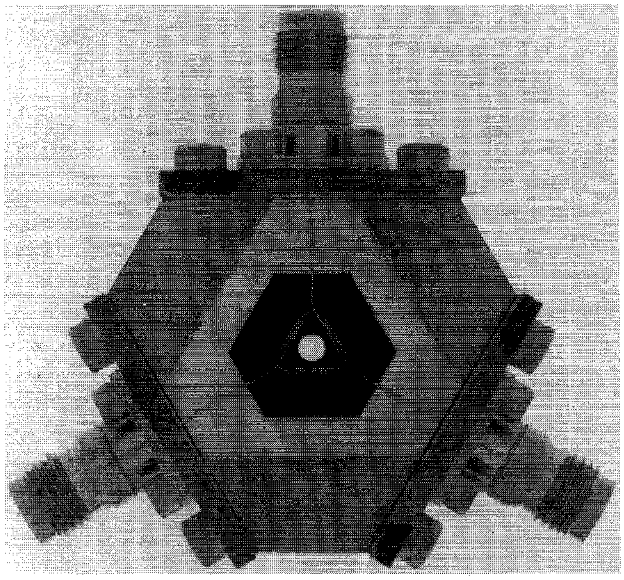
Fig. 7. Illustrative circulator performance, assuming linear variation of ϵ and δ about "band center"at $\eta = 2.4$.

36 dB) and return loss (from 46 to 26 dB) over the band of interest. Second, a further degree of realism is introduced with the assumption that the phase shifters utilized are incapable of conforming accurately to the requirements represented in Fig. 6, but instead provide $\arg(\epsilon)$ and $\arg(\delta)$ which vary linearly with η, with appropriately favorable slopes, and satisfy the circulation condition exactly at only one point, namely at "band center" $\eta = 2.4$. In this case the region of favorable circulation (insertion loss <0.5 dB and isolation >15 dB) is reduced to ±13%. The results are shown in Fig. 7. We note that these predictions, while certainly encouraging, result from a number of somewhat arbitrary assumptions selected for this illustration. The model is capable of yielding still better performance, approaching the ideal cited above, when optimized for a particular combination of bandwidth, circuit style and size, T junction and differential phase shift design, and other specifications.

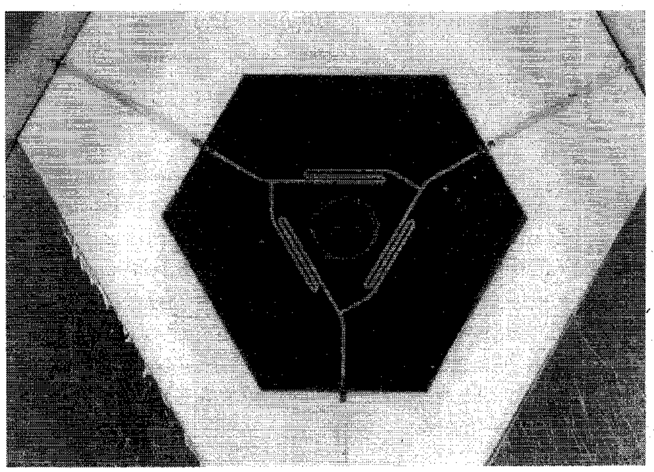
To complete the present illustration, we note that differential phase shifter designs which have been investigated up to the present are ferrite-loaded stripline comb-line filters [3] and ferrite-substrate microstrip meander lines. Future invention and development of this general class of devices will probably be associated with specific system requirements. For the T junctions, the reactive loading example cited above leads to the following illustrative specifications: for a microstrip system based on 50 Ω transmission lines, in a frequency band centered at, say, 10 GHz, with the parameters $\eta = 2.4$, $\zeta/\eta = 2/3$ as cited above, shunt C is 0.764 pF and series L is 1.27 nH (see Fig. 3; for design purposes these are favorably small compared to the characteristic transmission-line parameters per unit length, $C/\ell = 2.11$ pF/cm and $L/\ell = 5.29$ nH/cm if the substrate effective dielectric constant $\kappa_{\rm eff} = 10$ is assumed).

V. Experiments

Our experimental program to date has been directed partly toward verification of the ring-network circulator principle and partly toward devising and developing practical planar circulator structures based on that concept. We have employed



(a)



(b)

Fig. 8. (a) Photograph of a laboratory prototype microstrip ring-network circulator with ferrite substrate and meander-line nonreciprocal phase shifters. The major dimension between the connectoı center pins is 2 inches. (b) Enlarged view of the ring network.

a known class of planar nonreciprocal phase shifters, namely the microstrip meander line on a magnetized ferrite substrate. Fig. 8(a) shows a circulator prototype mounted in a laboratory test fixture; Fig. 8(b) is an enlarged view of the ring network. The "ferrite" (actually, YIG) [9] is Trans-Tech G-113; the ferrite wafer is 10 mils thick. It was magnetized circumferentially in its plane by means of current in a few turns of wire passed through the central hole. The measurements were performed with the current off and the ferrite magnetized in its remanent state; the arrangement is favorable for a fixed magnetless circulator or a circulator switch. Illustrative performance is shown in Fig. 9, indicating minimum insertion loss under 1 dB (cable, adapter, and other losses associated with the measurement configuration have been subtracted). Isolation bandwidth (>15 dB) of about ±1% is narrower than ring-network circulator capability because the optimum frequency-dependence of circulation conditions, discussed in

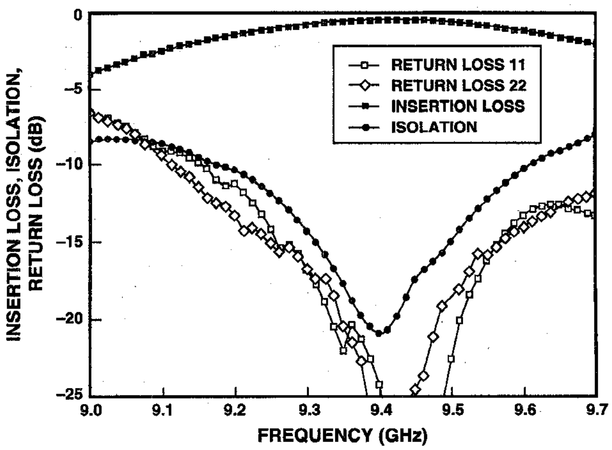


Fig. 9. Network-analyzer presentation of prototype circulator performance in the band 9.0–9.7 GHz. Cable and connector losses have been subtracted. Isolation is >15 dB over a ±1% band, and minimum insertion loss is under 1 dB.

Section IV, were not yet well approximated. The full realization of the potential ring-network circulator performance in bandwidth, insertion loss, and other specifications is our continuing objective.

VI. Conclusion

For the present era of thin-substrate integrated microcircuit technology, it is generally acknowledged that the resonant-type circulator [4] tends to suffer from inconvenient size, weight, and complexity. The ring-network circulator concept opens up an extensive range of design parameters and freedom from those vexing limitations, new solutions to a number of specialized requirements, and a rigorous basis for design, prediction, and interpretation.

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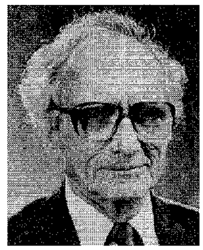
References

[1] J. A. Weiss, "Circulator synthesis," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 38–44, Jan. 1965.
[2] ——, "High-frequency circulator having a plurality of differential phase shifters and intentional mismatch means," U.S. Patent 3 304 519, assigned to MIT, Feb. 14, 1967.
[3] S. D. Ewing and J. A. Weiss, "Ring circulator theory, design, and performance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 623–628, Nov. 1967.
[4] H. Bosma, "On stripline Y-circulation at UHF," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 61–72, Jan. 1964.
[5] G. F. Dionne, D. E. Oates, and D. H. Temme, "Low-loss microwave ferrite phase shifters with superconducting circuits," in *IEEE Int. Microwave Symp.-Symp. Dig.*, San Diego, Paper TU1E-1, May 23–27, 1994, vol. 1, pp. 101–103.
[6] H. J. Carlin, "On the physical realizability of linear nonreciprocal networks," *Proc. IRE*, May 1955, vol. 48, pp. 608–616. "Principles of gyrator networks," *Proc. Symp. Modern Advances in Microwave Tech.*, Poly. Inst. Brooklyn, Nov. 1954, pp. 175–204.
[7] B. D. H. Tellegen, "The gyrator: A new electric network element," *Philips Research Reports*, vol. 3, p. 81, 1948.
[8] See, for example, Brian C. Wadell, *Transmission Line Design Handbook.* Norwood, MA: Artech House, 1991, Section 5.5, pp. 10–12, and references cited therein.
[9] Trans-Tech, Inc., 5520 Adamstown Rd., Adamstown, MD 21710. TT G-113 is a polycrystalline yttrium-iron garnet (YIG). At room temperature: Saturation magnetization $4\pi M_s = 1780$ Oe, coercive field $H_c = 0.45$ Oe, and dielectric constant $\epsilon_r = 15.0$.



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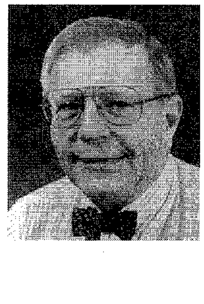

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