Performance Capabilities of the Ring Network Circulator for Integrated Circuits

Jerald A. Weiss* & Gerald F. Dionne

Lincoln Laboratory, Massachusetts Institute of Technology
Lexington, Massachusetts 02173

Abstract

The theoretical model of a ring network junction circulator introduced in 1965 is re-examined 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.

1. 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 constituting a three-port junction circulator (see Fig. 1). The principle is particularly applicable to miniature planar circuit design, but the formulation is general and valid for any type of microwave or millimeter-wave transmission medium. 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 principle, but also to explore whether useful analogies might be found between the parameters of the ring-network and those of the resonant (Bosma) type [4] or other junction circulators.

* Also affiliated with the Department of Physics, Worcester Polytechnic Institute, Worcester MA 01609.

The logic of the analysis was formulated to assure that no physically realizable, ideally lossless embodiment of the network would escape consideration. As shown in Appendix II of Ref. 1 and summarized briefly below (Sec. 4), a straightforward scattering formulation of clockwise- and counterclockwise-propagating partial waves leads to a characterization of the differential phase shifters in terms of assumed scattering parameters of the T junctions such that, assembled into a ring network, they yield perfect circulation. Computations performed then with a range of examples showed that many did indeed exhibit circulation as expected; surprisingly, it was found that the magnitudes of nonreciprocity required were often unexpectedly small. This suggested a potential for circulator designs with highly improved efficiency in the use of gyrotropic material. Predictions as to bandwidth and other related charactistics of the model had not yet been explored at the time of those publications.

At that time, however, exploitation of the concepts of planar circuits, integration, and miniaturization was only just getting under way; thus, the potential advantages of the ring network were not so apparent, as compared with the supposed disadvantages of loss and complexity that may have been suggested by those initial designs. 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 high-coecivity hexagonal materials, miniature composite ferrite-semiconductor substrates, and the near prospect of low-loss high-temperature superconducting planar circuits [5], a new look into the possibilities and distinctive features of the ring network circulator is now warranted.

With this design principle the approaches to miniaturization and bandwidth optimization are placed on

CH3577-4/95/0000-0725$01.00 © 1995 IEEE

an entirely new and rigorous footing. Also, numerous potential benefits of this class of designs accrue because, in contrast to the customary resonant-type, the ring-network circulator lends itself naturally to magnetization in the plane of the substrate. Such a configuration has significant advantages in size, weight, and energy requirements of magnetizing structures; in reduced coercivity requirements for self-magnetized devices (having no external magnet structure); in high-speed, energy-efficient switching capability of reversible circulators; and in achievement of the maximum benefit of low insertion loss in circulators incorporating superconducting circuits.

We show that the theory leads to solutions representing a very wide, continuous range of circulator designs, and we show how it furnishes information and design strategies relating to frequency dependence, specifically to operational bandwidth, and to the influence of dissipative loss.

2. Basic analysis.

The general three-port junction can be characterized by a 3×3-dimensional scattering matrix. With the constraints of reciprocity, energy conservation, and geometrical symmetry the number of independent parameters is four real numbers, in the case of a two-fold symmetrical T junction, leading to specification of four complex scattering coefficients r, s, r_d, s_d (see Fig. 2) which form the basis of an individual circulator design. Two parameters characterize the nonreciprocal phase shifters; 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 in each sector of the ring. (The phase shifters are assumed matched and lossless; accounting of the influences of loss is performed at a later stage of the analysis.) 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 these relations, the coefficients are functions of the "internal" scattering coefficients r and s of the T junctions.

We present an example to illustrate how the design of a set of T junctions with prescribed scattering characteristics can be accomplished 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 (or with measured values) as to the dispersive properties of the components, the frequency-dependence of circulator performance can be evaluated.

3. Reactive loading of the T junction.

In the present specialized 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 T 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 a series inductor L connected from the junction to each of the three ports (shown in Fig. 2). We can investigate bandwidth properties of this model through the linear frequency-dependence of capacitive susceptance and inductive reactance, together with appropriate assumptions about dispersion in the phase shifters. (An alternative illustrative analysis, with scattering of the T junctions controlled by variation of the characteristic impedance of the symmetrical arms, was presented earlier, in Ref. 3.)

Let $\omega C Z_0 = \eta$ and $\omega L Y_0 = \zeta$, 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 leads to the following expressions for r and s.

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

where $j = \sqrt{-1}$.

4. Determination of circulator performance.

In Appendix II of Ref. 1, equations are derived which lead to the determination of the phase shifter parameters, namely ϵ and δ, which are assumed to be complex numbers of unit magnitude with phase angles $\arg(\epsilon)$ and $\arg(\delta)$ specifying respectively the average phase and (half-)differential phase change on clockwise and counterclockwise propagation through any of the three identical sectors of the ring. Analysis of the scattering of internal partial waves in the structure of Fig. 1 leads to the algebraic equation

$$A_8\epsilon^8 + A_6\epsilon^6 + A_4\epsilon^4 + A_2\epsilon^2 + A_0 = 0 \qquad (2)$$

where $A_{0,..,8}$ are functions of the "internal" scattering coefficients r,s of the T junctions (see Ref. 1, Appendix II, Eqs. 25). This quartic equation in ϵ^2 possesses four solutions, of which in general two lead to physically realizable circulators. With such suitable values of ϵ satisfying Eq. 2, the associated values of δ are determined by

$$\delta^3 = \frac{a_4\epsilon^4 + a_2\epsilon^2 + a_0}{a_3\epsilon^3 + a_1\epsilon} \quad (3)$$

where the coefficients $a_{0,..,4}$ are again functions of the assumed r,s (Ref. 1, Appendix II, Eqs. 21). The courses of arg(ϵ) and arg(δ) for two acceptable solutions of Eqs. 2 and 3 for which $|\epsilon| = |\delta| = 1$, as functions of η, are shown in Fig. 3. For the present illustration we have assigned the ratio $\zeta/\eta = 2/3$ for the inductive and capacitive loading. We now select a range of Solution 1 in the interval 2.2< η <3.0 for our illustration because it exemplifies the capability for circulation with small amounts of differential phase. [In Fig. 3, note that arg(δ) declines from 7.2° to 2.1°. In that range the corresponding arg(ϵ) varies from 269.8° to 300.5°]. 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 due to the arbitrary choice of our range of attention: about ±15% in this example). Such an ideal is realistically 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 two examples.

First, we incorporate a small dissipative loss in the propagation constants of the phase shifters, leading to a minimum insertion loss of about 0.2 dB. The result is correspondingly degraded isolation (now ranging from 56 to 36 dB) and return loss (46 to 26 dB) over the band of interest. Next, 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. 3, but instead provide arg(ϵ) and arg(δ) which vary linearly with η and satisfy the circulation condition exactly at only one point, namely at "band center" $\eta = 2.6$. In this case the region of favorable circulation (insertion loss <0.5 dB and isolation >15 dB) is reduced to ±7.3%. The results are shown in Fig. 4. 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 shifter designs, 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 (Ref. 3), ferrite-substrate microstrip meander lines, and perhaps others. 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 frequency-dependent specifications: for a microstrip system based on 50 Ω transmission lines, in a frequency band centered at, say, 10 GHz, with the parameters $\eta = 2.6$, $\zeta/\eta = 2/3$ as cited above, shunt C is 0.828 pF and series L is 1.38 nH (see Fig. 2; to be compared with the characteristic C = 2.11 pF/cm and L = 5.29 nH/cm if the substrate effective dielectric constant $\kappa_{eff} = 10$ is adopted).

5. Conclusion.

For the present era of thin-substrate integrated microcircuit technology, it is generally acknowledged that the conventional resonant-type circulator 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.

6. Acknowledgments.

The authors wish to acknowledge valuable consultations and encouragement by D.H. Temme, and in particular his initiative in an experimental component of this project. We also acknowledge helpful technical support by D.E. Oates and excellent technical assistance by L.S. DiPalma.

References

1. J.A. Weiss: "Circulator Synthesis"; IEEE Trans. MTT **13** 38-44 (Jan. 1965).

2. U.S. Patent No. 3,304,519 Feb. 14, 1967: "High-frequency circulator having a plurality of differential

phase shifters and intentional mismatch means"; J.A. Weiss (assigned to MIT).

3. S.D. Ewing & J.A. Weiss: "Ring Circulator Theory, Design, and Performance"; IEEE Trans. MTT **15** 623-628 (Nov. 1967).

4. H. Bosma: "On Stripline Y-Circulation at UHF"; IEEE Trans. MTT **12** 61-72 (Jan. 1964).

5. G.F. Dionne, D.E. Oates & D.H. Temme: "Ferrite-Superconductor Microwave Phase Shifters"; IEEE Trans. Magn. **30** 4518-20 (Nov. 1994).

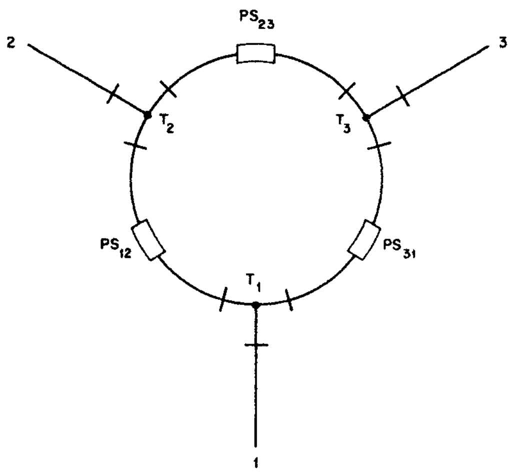

Fig. 1. Schematic diagram of the ring-network circulator. T and PS denote respectively symmetrical T junctions and nonreciprocal phase shifters.

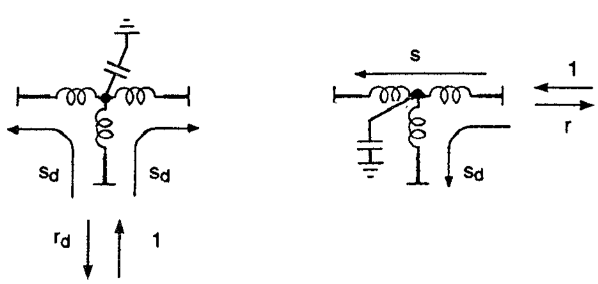

Fig. 2. Definitions of the scattering coefficients r, s, r_d, s_d of the symmetrical T junction.

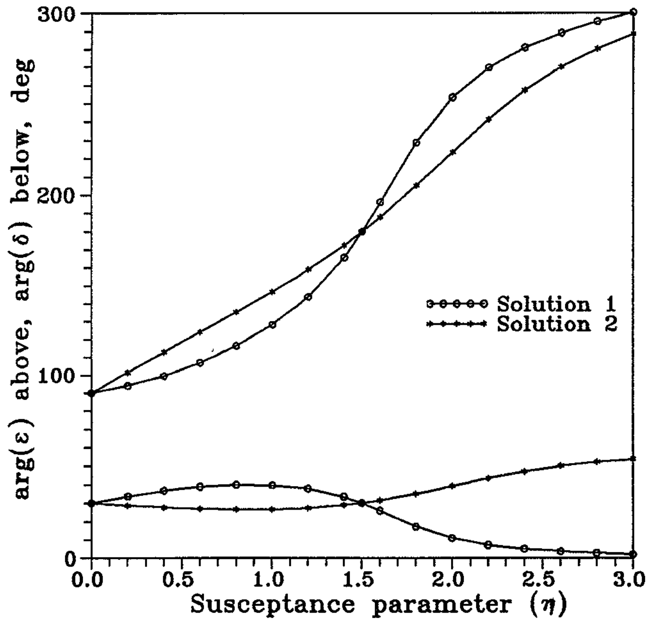

Fig. 3. Circulator solutions: mean phase arg(ϵ) and (half-)differential phase arg(δ) of the phase shifters as functions of the parameter η. The assumed ratio of T junction inductive reactance and capacitive susceptance parameters $\zeta = \omega L Y_0$ and $\eta = \omega C Z_0$ respectively, is $\zeta/\eta = (2/3)$.

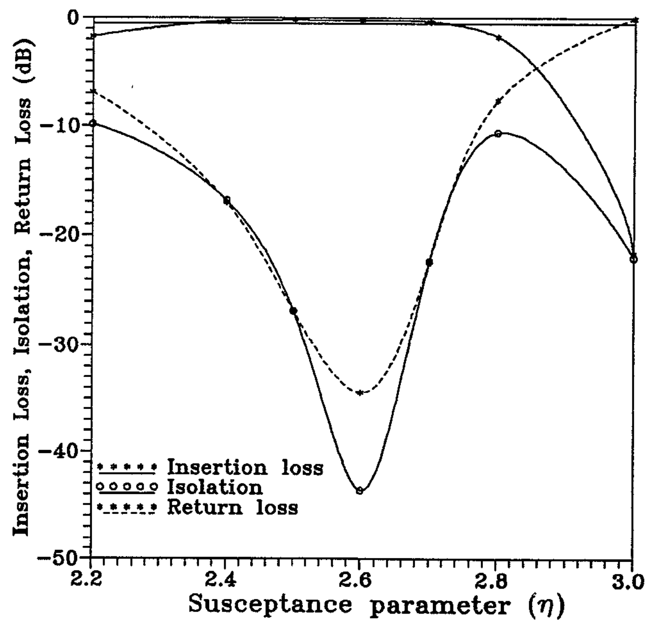

Fig. 4. Illustrative circulator performance, assuming that ϵ and δ satisfy the circulation condition exactly only at band center, namely $\eta = 2.6$, and vary linearly about that point with "optimum" slopes (see Fig. 3). Bandwidth for insertion loss <0.5 dB is ±7.3%.