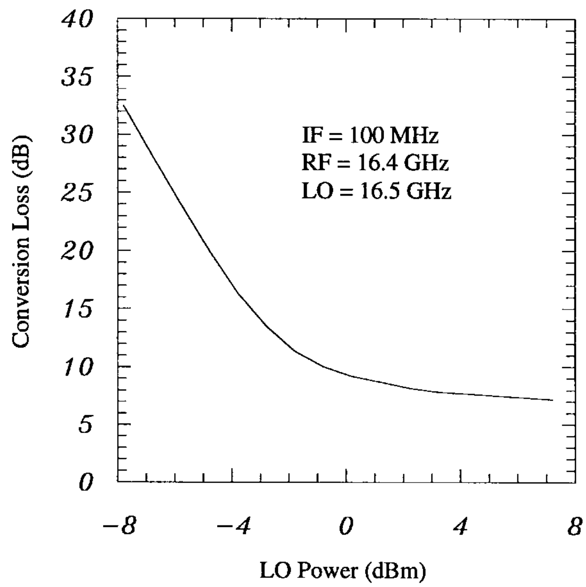

Fig. 6. Measured conversion loss versus LO pump power for the balanced mixer at 16.4 GHz.

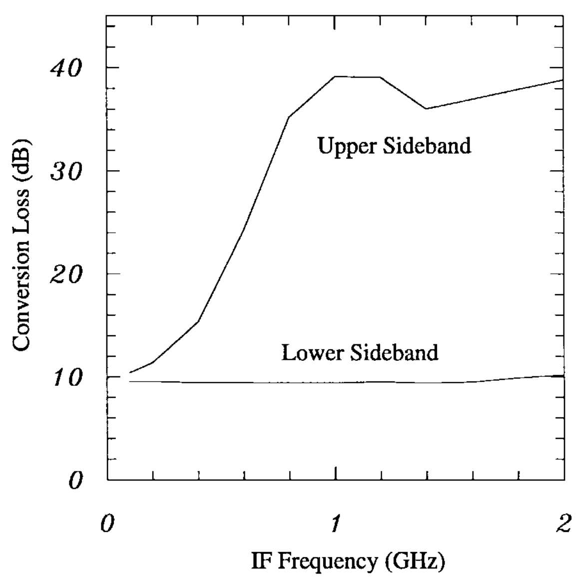

Fig. 7. Measured conversion loss versus the IF frequency for the single-sideband balanced mixer. The LO frequency is fixed at 17 GHz during the measurement.

circuit module. To our knowledge, the micromachined SSB mixer presents state-of-the-art conversion loss and image rejection. While this chip is physically larger than competitive GaA's FET-based MMIC's, it requires no dc power and only 1–2 mW of LO power. The membrane technology is fully compatible with the via-hole process in silicon, SiGe, GaA's and InP and can result in high performance IC's suitable for high volume productions for *Ka*, *V*, and *W*-band frequencies.

Acknowledgment

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A Method for Investigating a Class of Inhomogeneous Stripline Circulators

Giuseppe Macchiarella, Gian Guido Gentili, and Alberto Lobina

***Abstract*—Broad-band stripline circulators are studied by means of a mixed numerical technique which employs both Boundary Integral and Segmentation methods; this technique allows the analysis of planar circuits where the substrate is constituted by several regions with arbitrary shapes and different electrical properties.**

It is known that tracking circulators require matching structures because they present a low-gyrator impedance (real and almost constant in an octave frequency band). The matching structures (generally tapers or multisection's transmission line transformers) must be realized on a reciprocal substrate. The overall device (circular disk on ferrite substrate and matching structure on dielectric substrate) constitutes a planar circuit with an inhomogeneous medium.

The method of study presented here allows the determination of the overall impedance matrix of the planar circuit constituted by the nonreciprocal disk with sections of striplines connected to each port; in this way, the discontinuities between reciprocal and nonreciprocal medium are included in characterization of the overall device. Moreover the accuracy of the representation is increased. In fact, the coupling ports of the overall device may be located at a suitable distance from the disk boundary where higher-order modes excited by the discontinuities have been sufficiently attenuated and only the TEM mode is present on the striplines (which is the only one considered in the design of the matching structures).

***Index Terms*—Boundary elements, planar circulators, stripline devices.**

I. Introduction

Intrinsic wide-band stripline circulators were proposed in [1] and since that time this kind of device (often referred to as a tracking circulator) has been deeply investigated [2]–[5]. It is now well known

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that with proper design, intrinsic circulation (i.e., gyrator impedance [4] approximately real and constant with frequency) is obtainable in approximately an octave frequency band.

A specific feature of tracking circulators is the large widths of coupling ports, which determine low characteristic impedance at the coupling striplines. It is then necessary to introduce impedance-matching structures to obtain the usual 50-Ω impedance level at the input connectors of the overall device. Various examples of matching networks are shown in the literature, such as the taper [1] and the multisection's quarter-wave transformer [2]. However, in all cases the reference planes of the circulator coupling ports are taken at the disk boundary, where the ideal gyrator impedance of the circulator is defined. Such an approach does not take into account the effect of the discontinuity between the stripline and the circular disk which is the higher-order mode excited at the junction.

In order to include the discontinuity contribution into the gyrator impedance evaluation the reference plane of the circulator should be taken along the outgoing striplines at a suitable distance from the disk boundary where the electromagnetic field is practically of a pure TEM mode. Following this approach, a problem arises for computing the gyrator impedance; in fact, the overall structure is no longer homogeneous—there is a magnetized ferrite under the disk circulator and an isotropic dielectric under the striplines. As a consequence, the Contour Integral method, which is the most common numerical method for solving arbitrarily shaped planar circulators [7], cannot be directly applied.

A mixed approach is proposed in this work: first, the circular disk (nonreciprocal circuit) and the stripline sections (reciprocal circuits) are analyzed separately by means of the Contour Integral method; then, the impedance matrix of the overall planar circuit is obtained by applying the segmentation method [8] at the junction between the disk and the striplines.

The background of the two methods are briefly outlined in Section II, together with their combination for representing the overall planar circuit. In Section III the effects of the above-described discontinuities are analyzed in the case of a typical tracking circulator design.

II. Method of Characterization

The structure of the circulator considered here is represented in Fig. 1, together with the relevant geometrical parameters; the structure is assumed planar, i.e., the dimension b is small enough to make the variation of the electromagnetic field in the direction perpendicular to the plane negligible. All along the boundary, where the coupling ports are not present, a magnetic wall is assumed; at the coupling ports (1, 2, and 3 in Fig. 1) only the TEM mode of the ideal triplate-type waveguide is assumed to be present (as a consequence, the current density distribution is uniform along each port). Note that the overall device considered here is an inhomogeneous planar circuit because the coupling striplines are filled with an isotropic dielectric material while the circulator disk is embedded into an anisotropic magnetized ferrite.

For characterizing the three-ports' circulator, the overall impedance matrix $\boldsymbol{Z_t}$ of order 3 can be used; however, for the inhomogeneity of the structure, its computation cannot be directly performed through some usual approach, neither analytical (the eigenfunctions expansion in [6]) nor numerical (the Contour Integral).

A simple mixed numerical approach is then proposed in this paper. The planar structure is first subdivided into its reciprocal and nonreciprocal substructures, as shown in Fig. 1 (note that each component is a homogeneous planar circuit). After dividing the boundary of each subregion into segments, the impedance matrices of all the substructures are then evaluated by means of the Contour Integral method. The impedance matrix of the overall structure is finally evaluated by combining all the substructures impedance matrices by means of the Segmentation method.

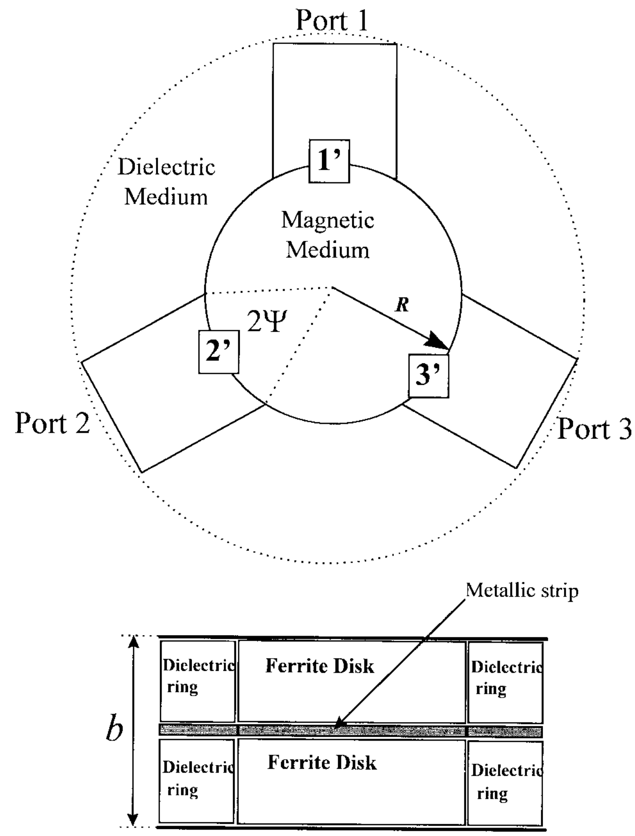

Fig. 1. Geometry of the tracking circulator.

In the following, "circulator" refer to the overall device, while the nonreciprocal region is called "disk."

A. The Contour Integral and Segmentation Methods

The contour integral method (CIM) is a powerful technique for analyzing arbitrarily-shaped homogeneous planar circuits, both with isotropic or anisotropic spacing media. Many works may be found in the literature where CIM is thoroughly explained and analyzed [3]–[5]. Recently, a novel formulation of this method has been proposed [9], [11], which allows for more stable results with a reduction of the computing time, especially for nonreciprocal planar circuits (circulators).

In order to apply CIM, the contour of the planar circuit is approximated by a finite number of straight segments. Those belonging to the coupling ports are characterized by a uniform current density normally injected. For all the remaining segments, a magnetic wall is assumed (the normal current density is null).

The solution which is generally obtained from CIM is the impedance matrix $\boldsymbol{Z_t}$ of order M, where M is the total number of the segments belonging to all ports [8]. A circuit impedance matrix $\boldsymbol{Z}$ of order equal to the number of ports of the planar circuit may be then derived by averaging the V or the current distribution along each port.

The segmentation method was originally proposed in [8] for analyzing planar circuits whose shape is decomposable into simple regular polygons for which analytical characterization is easily obtainable. A more efficient formulation was subsequently proposed in [10], which makes use of impedance matrices only, with a relevant shortening of the computing time.

B. Implementation of the Mixed Method

Let's assume that by means of CIM the impedance matrices $\boldsymbol{Z_C}$ and $\boldsymbol{Z_S}$ of disk and striplines, respectively, (Fig. 1) have been computed. Letting N be the number of segments over each port of the disk and the striplines, the order of $\boldsymbol{Z_C}$ is then $3N$, while that of $\boldsymbol{Z_S}$ is $2N$ (Fig. 2). The explicit forms of a generic $M \times M$ impedance matrix of a reciprocal $(\boldsymbol{Z_S})$ and nonreciprocal $(\boldsymbol{Z_C})$ planar circuit can be found in [8]. Following the formalism introduced in [10], the ports of the circuit in Fig. 1 are classified into external (1, 2, 3) and connected (1′, 2′, 3′). The following matrices of order $3N$ are then introduced (the elements not reported are zeros):

$$\underline{\underline{Z}}_{pp} = \begin{vmatrix} \underline{\underline{Z}}^s_{11} & & \\ & \underline{\underline{Z}}^s_{11} & \\ & & \underline{\underline{Z}}^s_{11} \end{vmatrix}, \qquad \underline{\underline{Z}}_{pq} = \begin{vmatrix} \underline{\underline{Z}}^s_{12} & & \\ & \underline{\underline{Z}}^s_{12} & \\ & & \underline{\underline{Z}}^s_{12} \end{vmatrix} \tag{1}$$

where $\underline{\underline{Z}}^s_{11}$ and $\underline{\underline{Z}}^s_{12}$ (of order N) are the components of $\boldsymbol{Z_S}$:

$$Z_s = \begin{vmatrix} \underline{\underline{Z}}^s_{11} & \underline{\underline{Z}}^2_{12} \\ \underline{\underline{Z}}^2_{12} & \underline{\underline{Z}}_{11} \end{vmatrix}. \tag{2}$$

The overall $\underline{\underline{Z_t}}$ matrix at the external ports is then given by the following expression:

$$\underline{\underline{Z_t}} = \underline{\underline{Z}}_{pp} - \underline{\underline{Z}}_{pq} \cdot (\underline{\underline{Z}}_{pp} + \underline{\underline{Z}}_c)^{-1} \cdot \underline{\underline{Z}}_{pq}. \tag{3}$$

From $\underline{\underline{Z_t}}$ the circuit impedance matrix of order 3 (which is three-fold symmetric) can be obtained as follows. The external ports of the overall device (the disk with the coupling stripline sections) are assumed far enough from the disk boundary that only the TEM mode of the ideal triplate-type waveguide is present at each port. Then the voltage along the ports (1, 2, 3) is constant and the total current is obtained by summing all the contributions from the segments into which each port is subdivided. From the circuit point of view this means that all the subports corresponding to the segments along each external ports are in parallel. It is then convenient to perform the computations in terms of the admittance matrices. The three independent elements of the overall circuit admittance matrix $\boldsymbol{Y} = [y_{ij}]$ (three-fold symmetric) of the device is then readily obtained from $\underline{\underline{Y_t}}$ (the inverse of $\underline{\underline{Z_t}}$) as

$$y_{11} = \sum_{i=1}^{N}\sum_{j=1}^{N} Y_t^{11}(i,j) \quad y_{12} = \sum_{i=1}^{N}\sum_{j=1}^{N} Y_t^{12}(i,j)$$
$$y_{13} = \sum_{i=1}^{N}\sum_{j=1}^{N} Y_t^{13}(i,j) \tag{4}$$

where $\underline{\underline{Y_t}}^{11}, \underline{\underline{Y_t}}^{12}, \underline{\underline{Y_t}}^{13}$ are the components of order N of $\underline{\underline{Y_t}}$. The circuit impedance matrix $\boldsymbol{Z}$ can be finally computed by inverting $\boldsymbol{Y}$.

Some considerations on the application of this technique are now necessary. One should observe that the technique proposed does not assume a specific electric or magnetic field at the junction between the stripline and the disk. On the contrary, the segmentation process combines electric and magnetic fields so that their tangential components are preserved at that interface. This "continuity condition" is imposed by averaging over each segment (and not over each port) and the accuracy can be increased by increasing the number of segments N. The segmentation process inherently takes into account the reactive field of higher-order modes excited at the junction.

The proposed procedure overcomes two limitations of the analysis in [6]. The first is the assumption of a pure-TEM field at the *interface* disk-stripline. The second is the assumption that the magnetic and electric field of such a TEM mode are constant over the *curved* part of the boundary corresponding to a port. This latter assumption is a very good approximation when the striplines are narrow, but this is not the case for tracking circulators. Thus, although the electric and magnetic fields of a TEM mode in the equivalent planar waveguides corresponding to the striplines are constant, when one evaluates them along the curved part of the boundary corresponding to a port, the fields are no longer independent on the curvilinear coordinate defined on the port. This second effect is also taken into account by the segmentation technique.

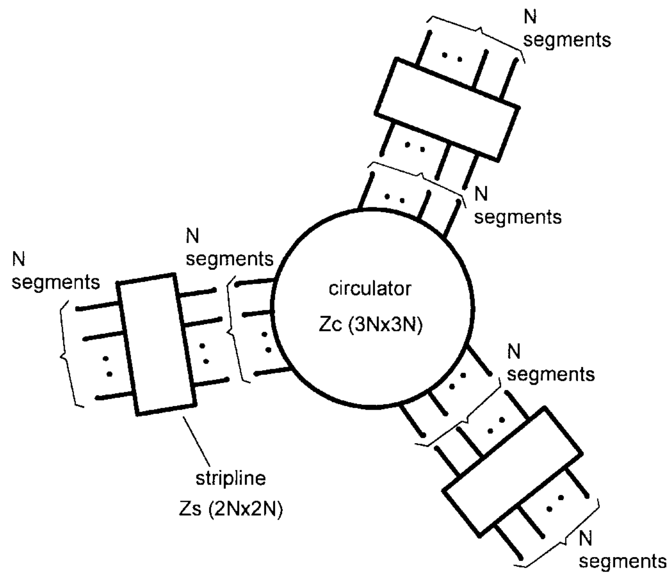

Fig. 2. Schematic of segmentation.

Note that eventually the proposed procedure can be applied also when the nonreciprocal part of the circulator has a noncircular shape. In this case, the analysis in [6] is no longer applicable.

III. Performance Evaluation of Tracking Circulators

The method discussed in the previous sections is applied to the tracking circulators' characterization. The design of this kind of device may be developed in several ways with the goal of obtaining the gyrator impedance which is approximately real and constant with frequency in an almost octave bandwidth. A typical design produces the following result (the geometrical parameters refer to Fig. 1):

$$\psi = 0.52; \quad \frac{R}{\lambda_{0f}} = 0.31; \quad \frac{f_0}{f_m} = 1.5; \quad \varepsilon_d \cong \varepsilon_f \tag{5}$$

where $\lambda_{0f} = \lambda_0 / \sqrt{\mu_{\text{eff}}\varepsilon_f}$ is the wavelength in the ferrite at frequency f_o (with μ_{eff} effective permeability of the ferrite, which depends on the Polder tensor elements μ and κ); f_m is the magnetization frequency, given by $\gamma \cdot \boldsymbol{M}_s$, with $\boldsymbol{M}_s$ saturation magnetization of ferrite material and $\gamma = 2.8$ MH/Oe; ε_d and ε_f are the relative dielectric constants of the outgoing striplines substrate (reciprocal) and of the ferrite, respectively.

The parameter which is usually adopted to characterize the behavior of the circulator is the gyrator impedance Z_{gyr}. For an ideal device, Z_{gyr} must be independent on frequency and equal to the characteristic impedance of the outgoing transmission lines. This parameter can be computed from the three independent elements of the overall impedance matrix $\boldsymbol{Z}$ [4]:

$$Z_{\text{gyr}} = Z_{11} - \frac{Z_{12}^2}{Z_{13}}. \tag{6}$$

The expected mismatch at the external ports of a circulator can then be represented by the reflection coefficient Γ_{gyr} given by:

$$\Gamma_{\text{gyr}} = \frac{Z_{\text{gyr}} - Z_c}{Z_{\text{gyr}} + Z_c} \tag{7}$$

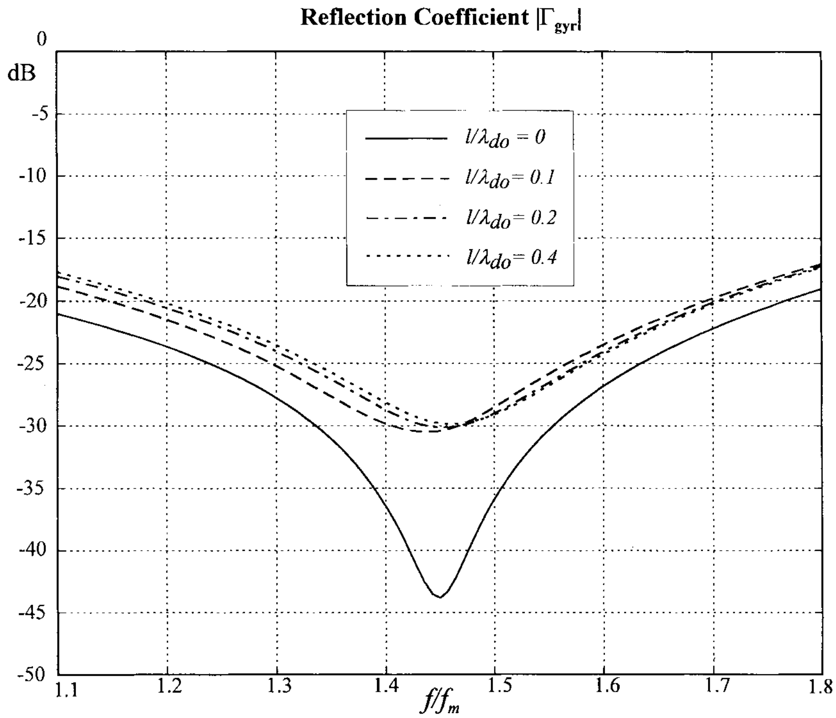

Fig. 3. Results obtained from simulations of the test-tracking circulator ($f_0/f_m = 1.5, \psi = 0.52, R/\lambda_{0f} = 0.31, \varepsilon_d/\varepsilon_f = 1$), for different lengths of the outgoing stripline section.

where Z_c is the characteristic impedance of the ideal stripline (triplate-type waveguide).

The overall circulator has been simulated using the proposed method with 42 segments along the disk boundary. Each inner port (assumed to be of circular shape) is defined by eight segments (which is then the value of N). The number of segments along the stripline boundary varies between 20–36, depending on the section's length l.

Several simulations have been performed, varying the normalized frequency f/f_m, for several normalized lengths l/λ_0 of the outgoing stripline sections.

The results obtained are summarized in Fig. 3, where $|\Gamma_{\rm gyr}|$ is reported versus f/f_m, for $l/\lambda_0 = 0, 0.05, 0.2, 0.4$. It is worth noting that results obtained with $l/\lambda_0 = 0$ correspond to Bosma's result.

A degradation of the performances can be first observed (i.e., the -20-dB bandwidth), with respect to the ideal case with $l/\lambda_0 = 0$ (circular disk alone), when the lines are considered (i.e., the discontinuities effects are included in the evaluation of $Z_{\rm gyr}$). This means that the -20-dB bandwidth of a device designed with classical numerical methods is generally overestimated of a factor ≈1.4.

Also, the expected convergence effect as the stripline section's length increases can be observed in Fig. 3. From a practical point of view, a value of l/λ_0 equal to 0.2 is sufficient to stabilize the parameters of the overall circulator.

IV. Conclusion

A method for analyzing inhomogeneous planar circuits constituted by interconnected homogenous regions (both reciprocal and nonreciprocal) has been presented which is based on the Contour Integral method for the evaluation of the impedance matrices of the homogeneous regions, and on the Segmentation method for combining these matrices. The method proposed has been applied to the study of tracking circulators in order to take into account the effect of the junction between the circular disk and the outgoing striplines. For stabilizing the computed parameters of the overall circulator, the normalized length l/λ_0 of the outgoing striplines must be at least 0.2.

The application of the method to the characterization of stub-loaded stripline circulators is currently under development.

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