Short Papers

Design and Fabrication of a Nonradiative Dielectric Waveguide Circulator

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***Abstract* —A technique for constructing a high-performance nonradiative dielectric waveguide (NRD guide) circulator for use at 50 GHz has been developed. A novel type of mode suppressor, which serves to reduce unwanted modes to a negligible level, has been devised and used to improve circulator performance significantly. A half-wavelength step transformer was installed at each port of the circulator to increase the operational bandwidth. The insertion loss of this fabricated circulator is less than 0.3 dB, and the 20 dB isolation bandwidth is about 2.6 GHz.**

Characteristics of the NRD guide circulator are analyzed based on an equivalent circuit representation. This analysis considerably facilitates the design procedure of the circulator.

I. Introduction

Because of their practical importance as nonreciprocal devices, circulators have been developed utilizing various transmission media such as metal waveguides, microstrips, finlines and image guides [1]–[4]. High-performance circulators are also required for nonradiative dielectric waveguide (NRD guide) integrated circuits, which have recently been proposed for millimeter-wave applications [5]. This paper describes the design and fabrication techniques for a practical NRD guide circulator for use at 50 GHz.

As described elsewhere [5], the NRD guide consists of rectangular dielectric strips sandwiched between two parallel metal plates, and features low transmission loss and no radiation at curved sections and discontinuities. Since the electric field in the NRD guide is predominantly parallel to the top and the bottom plates, the NRD guide is a typical E-plane circuit. Therefore, the NRD guide circulator resembles its waveguide E-plane counterpart in arrangement [6]. Large ripples, however, appeared when the forward and backward transmissions of a fabricated NRD guide circulator were measured. Careful examination of this phenomenon has revealed that the mode conversion between the operating mode and a parasitic mode is the main cause of the generation of these ripples. In order to eliminate the parasitic mode, a novel type of mode suppressor has been devised based on the $\lambda/4$ choke principle. The ripples almost completely disappeared, as expected, when the mode suppressors were incorporated into the circulator.

Band widening is another consideration when constructing practical circulators. Several techniques have been developed so far for this purpose. One of them is the modification of the ferrite resonator shape to adjust the resonant frequency of the in-phase mode [7]; another is the use of an impedance transformer of a half or quarter wavelength at each port of the circulator [8]–[10].

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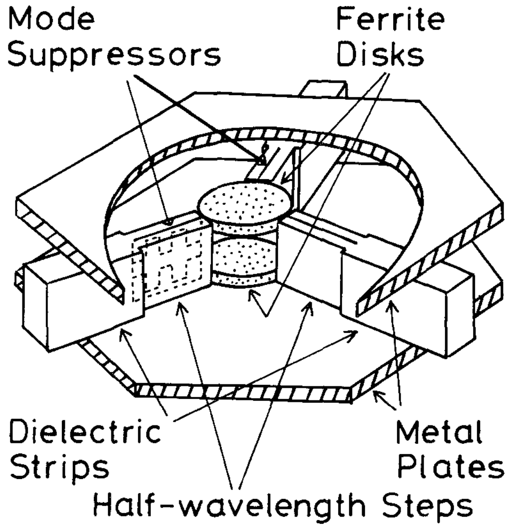

Fig. 1. Structure of the NRD guide circulator with half-wavelength steps and mode suppressors.

The latter technique was applied in the present case, since the required transformer could simply be realized by means of a half-wavelength step provided at the end of each port of the circulator. Performance of the fabricated circulator was found to be quite satisfactory; that is, the 20 dB isolation bandwidth and insertion loss were 2.6 GHz and 0.3 dB, respectively.

In order to establish a design theory, the NRD guide circulator is analyzed based on an equivalent circuit representation [11], [12]. The analysis is found to be especially useful for predicting the optimum step width needed for band widening of the circulator.

II. Preliminary Consideration

Since the NRD guide has the electric field predominantly parallel to the top and the bottom plates, it is a so-called E-plane circuit. Therefore, the NRD guide circulator takes a form similar to its waveguide E-plane counterpart, as shown in Fig. 1 [6]. However, large ripples appeared as shown in Fig. 2 when the insertion loss and isolation of the circulator were measured.

Careful examination has revealed that such ripples are related to the generation of a parasitic mode in the NRD guide. The operating mode of the NRD guide is the so-called LSM_{01} mode, which resembles the TE_{10} waveguide mode in field configuration, as shown in Fig. 3(a). In addition to the LSM_{01} mode, the LSE_{01} mode, which resembles the TM_{11} waveguide mode in field configuration, as shown in Fig. 3(b), can also exist in the NRD guide as a nonradiative mode. It should be noted that the LSE_{01} mode has a lower cutoff frequency than the LSM_{01} mode. Since such a parasitic mode has already been found at NRD guide bends [13], it is natural to infer that the same parasitic mode can exist in the NRD guide circulator as well.

The ripples observed in loss characteristics of the circulator can be interpreted as being caused by the mode conversion between the two nonradiative LSM_{01} and LSE_{01} modes in the

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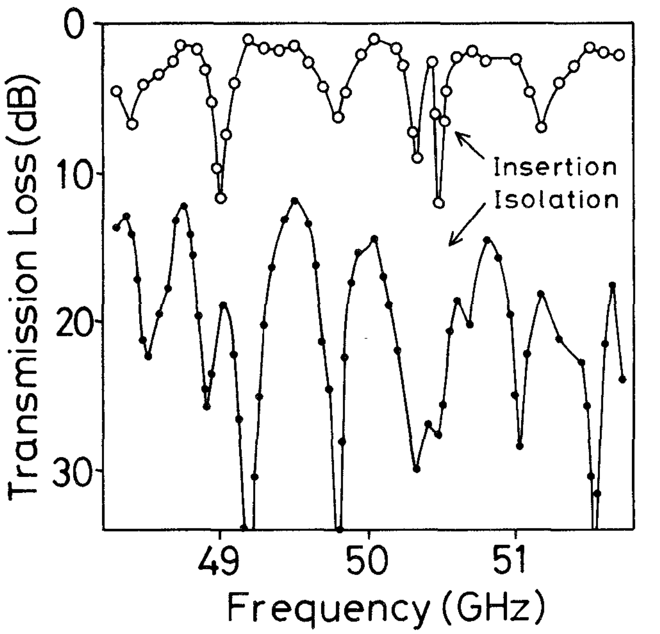

Fig. 2. Measured insertion loss and isolation of the NRD guide circulator without mode suppressors.

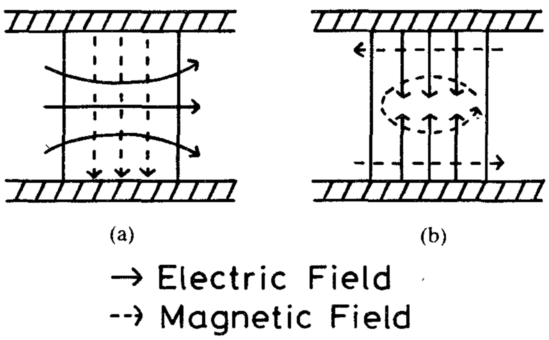

Fig. 3. Rough sketches of field lines in the transverse plane of the NRD guide. (a) LSM_{01} mode. (b) LSE_{01} mode.

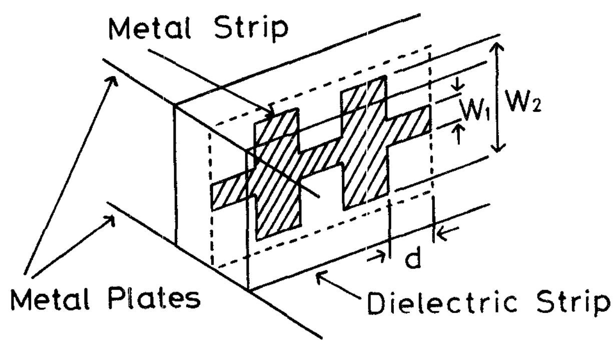

Fig. 4. Structure of the mode suppressor. Typically, $d = 0.95$ mm, $W_1 = 0.4$ mm, and $W_2 = 2.5$ mm at 50 GHz.

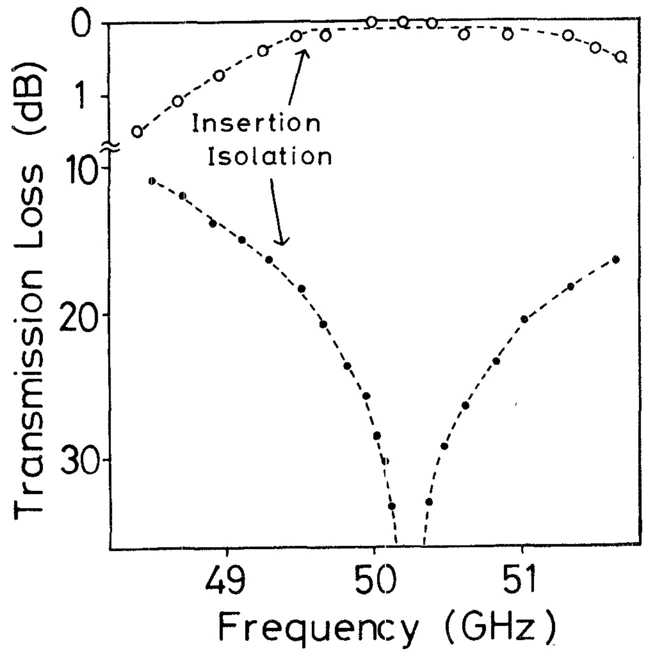

Fig. 5. Measured insertion loss and isolation of the NRD guide circulator with mode suppressors.

NRD guide. This phenomenon can be enhanced by the presence of the transition horns which are used to connect the circulator to the measuring system. These horns are so designed that only the operating LSM_{01} mode is matched to the metal waveguide with return loss higher than 24 dB, but the parasitic LSE_{01} mode is almost entirely reflected back [14]. The multiple reflection of the parasitic mode between the transition horns can produce a complicated interference pattern on the loss curves of the circulator. Therefore, suppression of the parasitic mode is required to fabricate a practical NRD guide circulator.

III. NRD Guide Circulator with Mode Suppressors

A. Mode Suppressor

A mode suppressor has been devised for eliminating the above-mentioned parasitic mode. It is a shaped metal strip inserted at the midplane of the dielectric strip perpendicularly to the metal plates as shown in Fig. 4. The operating LSM_{01} mode is never affected by the presence of the mode suppressor, since its electric field is normal to the metal strip. However, the cross-polarized LSE_{01} mode is below cutoff, because its electric field has a component parallel to the metal strip. Unfortunately, however, the presence of the metal strip induces the TEM wave along the metal strip. In order to avoid the generation of such an unwanted wave, the metal strip is shaped into a $\lambda/4$ choke structure for the TEM wave. The mode suppressor is simple in structure, easy to fabricate, and efficient in eliminating the unwanted mode, leaving the operating mode unaffected, as will be seen in the next section. The mode suppressors were fabricated by the conventional photoetching technique on a 0.13-mm-thick dielectric substrate whose dielectric constant is 2.6 and inserted at the end of each dielectric strip where the parasitic mode seems to be generated. The mode suppressor of a five-step choke, 4.8 mm in total length, has been found to be sufficient to reduce the parasitic modes to a vanishing level.

B. Measured Performance

The circulator provided with the mode suppressors for use at 50 GHz was fabricated. Polystyrene strips ($\epsilon_r = 2.56$) 2.7 mm in height and 2.4 mm in width were used. A pair of YIG ferrite disks ($4\pi Ms = 1800$ G, $\epsilon_r = 15.0$) 3.37 mm in diameter and 0.342 mm in thickness was supported by a foamed polystyrene block ($\epsilon_r = 1.03$) as shown in Fig. 1 and its resonant frequency was measured to be 50.4 GHz in the unbiased state. This resonant frequency is almost coincident with the center frequency of the circulator in the present case. The magnetic bias of 1320 Oe was applied perpendicular to the ferrite resonator so as to yield the optimum circulation.

Loss measurements were made by comparing transmissions of the circulator with that of the straight strip of the same length, and the results are shown in Fig. 5. No ripples appear in this case; hence the parasitic mode can be considered to be almost completely eliminated. The 20 dB isolation bandwidth was measured to be 1.4 GHz, with maximum isolation at the resonant frequency of the unbiased ferrite resonator. The insertion loss was found to be less than 0.3 dB over the 20 dB isolation bandwidth. This loss value is comparable to that of the conventional waveguide circulator [1], in spite of the possible increase in loss due to the inserted mode suppressors.

Thus, the NRD guide circulator has been improved to a practical level as far as loss characteristics are concerned. The mode suppressor is essential for the NRD guide circulators, and can be expected to be applied to other NRD guide circuit components as well.

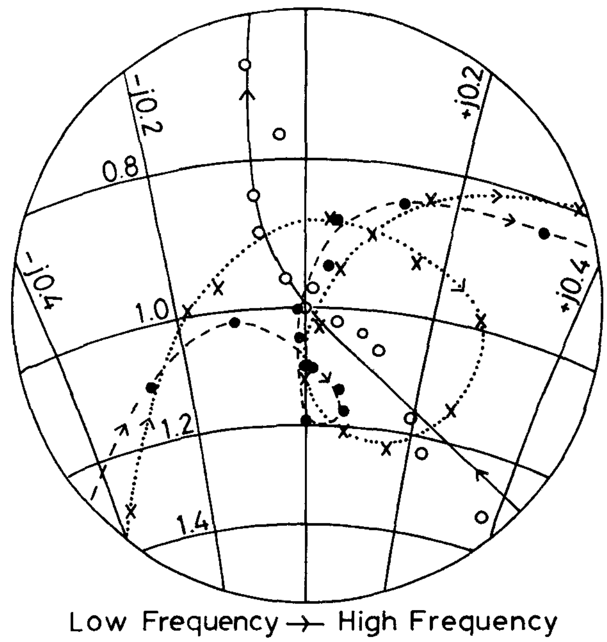

Fig. 6. Measured input impedance loci of the NRD guide circulator: O for the circulator with mode suppressors, and ● and × for the circulators with half-wavelength steps 1.9 mm and 2.0 mm in width, respectively.

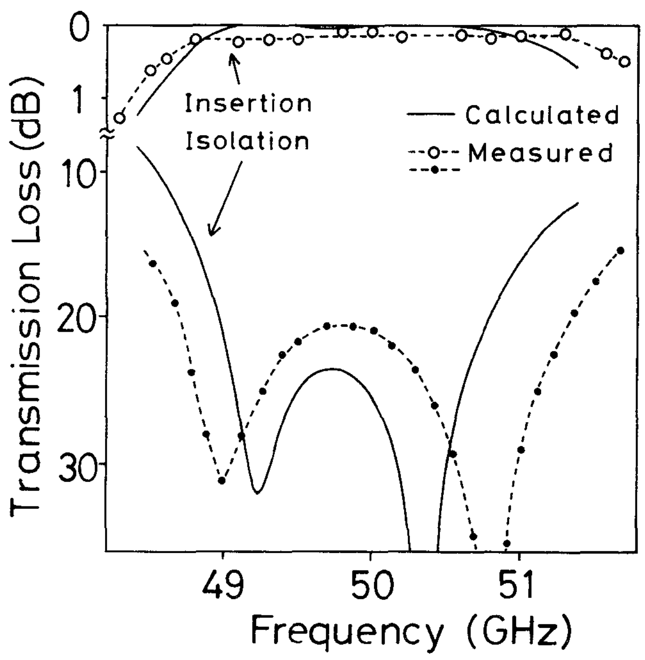

Fig. 7. Measured and calculated insertion loss and isolation of the NRD guide circulator with half-wavelength steps and mode suppressors.

IV. Band Widening of the NRD Guide Circulator

A. Measurement

Since bandwidth properties of the circulator can be estimated in terms of the input impedance, the input impedance of the NRD guide circulator discussed in the previous section was measured as a function of frequency. In the measurements, two other ports were matched and the input impedance was referred to the junction plane between the dielectric strip and the ferrite resonator. Smith chart plots of the results are illustrated by the solid curve in Fig. 6. The measured impedance locus is a simple curve, but it should describe a small loop around the center of the Smith chart for broad-band operation of the circulator. A conventional technique for such a purpose is to use half-wavelength resonators [10] located at a suitable position on the waveguides. The resonator can be a narrower or wider waveguide section of a half-wavelength. A preliminary experiment has shown that half-wavelength steps are as effective as half-wavelength resonators in the present case.

Two types of steps, 1.9 mm and 2.0 mm in width, were tested. The measured impedance loci described loops on the Smith chart as expected, as shown by dotted curves in Fig. 6. With the wider steps, the loop is larger in diameter, and the intersection of the locus is off center on the Smith chart. With the narrower steps, however, the loop is smaller in diameter and the intersection of the locus is very close to the center of the Smith chart. The latter case is favorable for band widening the circulator; that is, the circulator can be matched at two frequencies corresponding to the intersection of the locus. Moreover, the impedance properties are not much different from the matched state between these two frequencies, because of the small diameter of the locus.

The measured insertion loss and isolation of this modified circulator are shown by dotted curves in Fig. 7. Dips below 30 dB can be observed on the isolation curve at two frequencies where the circulator is matched. These curves should be compared with those of the prototype circulator plotted in Fig. 5. The 20 dB isolation bandwidth is 2.6 GHz, which is around twice as large as that of the prototype.

The insertion loss is less than 0.3 dB over the 20 dB isolation bandwidth. The fabricated circulator is optimum as far as the 20 dB isolation bandwidth is concerned, since the greater the separation of the two dips on the isolation curve, the poorer the isolation between them.

At this point, it may be important to say that the center frequency of the prototype circulator should be chosen to be slightly higher, say, by about 0.7 GHz, than the desired center frequency of the band-widened circulator, since the bandwidth is extended mainly toward the lower frequency side by the present techniques, as can be seen by comparing Fig. 5 and Fig. 7.

B. Equivalent Circuit Analysis

In order to understand the operation mechanism of the NRD guide circulator and develop a design theory, analysis is made based on an equivalent circuit representation. In general, the circulator can be represented in terms of a three-by-three scattering matrix [11], [12]. Each matrix element can be determined, as discussed by Goebel and Schieblich [12], if the resonant frequencies of the clockwise and counterclockwise rotating modes in the dc biased ferrite resonator are calculated or measured. In addition, the effect of discontinuity between the dielectric strip and the ferrite resonator can be taken into account by introducing a small segment of the dielectric strip of normal cross-sectional size between each dielectric strip and the ferrite resonator. Typically, the length of such a small segment was found to be 0.7 mm.

Now, characteristics of the NRD guide circulator can be simulated in terms of various given parameters. Among them, the parameters which have to be measured are only the resonant frequencies of the clockwise and counterclockwise rotating modes in the ferrite resonator and the length of the small dielectric segment.

The insertion loss and the isolation are calculated at 50 GHz for the circulator with the dielectric strip 2.4 mm in width and the half-wavelength steps 1.8 mm in width, and are plotted with solid curves in Fig. 7, in comparison with the results of measurement. Agreement between calculation and measurements is excellent, although the step width assumed in theory is slightly different from that used in measurement. This discrepancy between theory and measurement seems to be caused by unavoidable fabrication error related to the insertion of the mode suppressors and loss in the ferrite material. Nevertheless, the equivalent circuit analysis is very useful, since it can predict the optimum width of the half-wavelength steps as well as the performance characteristics of the circulator.

V. Conclusion

A high-performance NRD guide circulator has been constructed by incorporating mode suppressors and half-wavelength steps on the dielectric strips. The fabricated circulator has an insertion loss less than 0.3 dB and a 20 dB isolation bandwidth of about 2.6 GHz. Equivalent circuit analysis of the circulator has proved to be especially useful for predicting the optimum step width needed for band widening the circulator.

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Thick Circular Iris in a TE_{11} Mode Circular Waveguide

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Abstract —**The TE_{11} mode excitation of a concentric circular iris of finite thickness in a circular waveguide is analyzed by Galerkin's method with even and odd excitation. Agreement between calculated and measured dominant mode scattering parameters is generally within experimental accuracy.**

I. Introduction

The thick circular iris of Fig. 1 has an aperture of radius b, is of longitudinal thickness T, and is concentrically located in a circular waveguide of radius a. There is a transverse plane of symmetry through the center of the iris. Employing superposition, excitation of the iris from the left is equivalent to in-phase (even) excitation from both sides plus out-of-phase (odd) excitation from both sides [1, p. 354]. According to image theory, a shorting perfect magnetic conductor (tangential $\overline{H}=0$ or open circuit) placed at the symmetry plane in the center of the thick iris and excited from the left (Fig. 2) is equivalent to the even excitation case as far as the total fields to the left of the plane are concerned. Similarly, a perfect electric conductor (tangential $\overline{E}=0$ or short circuit) at the symmetry plane produces the same total fields to the left of the plane as the odd excitation case. Each of these problems is solved separately with the desired TE_{11} mode incident from the left. The total fields everywhere to the left of the symmetry plane in the thick iris problem are then given by the sum of the separate fields:

$$(\overline{E},\overline{H})_{\text{total}}=\frac{1}{2}(\overline{E},\overline{H})_{\text{even}}+\frac{1}{2}(\overline{E},\overline{H})_{\text{odd}}. \tag{1}$$

II. Analysis

The TE_{11} mode excitation of the infinitesimally thin circular iris is treated in [2]. Approximating the transverse electric field in the aperture ($z=0$) plane by a finite set of M TE_{1m} modes and N TM_{1m} modes of waveguide (b)

$$\overline{E}_{\text{aper}}(\overline{\rho})=\sum_{l=1}^{M}\tilde{V}_l^h\tilde{\overline{e}}_l^h(\overline{\rho})+\sum_{l=1}^{N}\tilde{V}_l^e\tilde{\overline{e}}_l^e(\overline{\rho}),\qquad \overline{\rho}\in S \tag{2}$$

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