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Proposed New Circulator with Coplanar Waveguide Structure

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A small circulator with a coplanar waveguide structure was confirmed to have nonreciprocal transmission characteristics by a high-frequency electromagnetic simulation based on a three-dimensional finite element method. The circulator consists of a hexagonal YIG ferrite substrate and a Y-junction with coplanar waveguide transmission lines. Operating at 7 GHz, the circulator has an insertion loss $|S_{21}|$ of 0.69 dB, isolation $|S_{31}|$ of 32.7 dB, return loss $|S_{11}|$ of 32.2 dB, and bandwidth of 77 MHz. The nonreciprocal operation of the circulator is attributed to the wavy nonuniform distribution of the electric field in the YIG ferrite substrate.

Key words: circulator, coplanar waveguide, YIG ferrite, transmission characteristics

1. Introduction

To achieve miniaturization, thickness reduction, and multi-functionalization of cellular phones, it is essential to reduce the size of the circulator/isolator, a key device in cellular phone sets, whose function is to control the transmission direction of microwave signals. Current circulator products designed with frequency of 2 GHz and below are of the lumped-element circuit type, because this type is effective for reducing the device size in spite of its relatively complex structure at low frequencies. The C-band (4-8 GHz) is scheduled to become available for the use of future cellular phone systems or wireless systems in the home. At C-band frequencies, distributed-element-circuit-type circulators are likely to become popular because their structure is so simple.

We have successfully proposed a new distributed-element-circuit-type circulator with a microstrip line structure [1), 2)]. The circulator has a size of 5 mm (W) × 6.5 mm (D) × 1.0 mm (H), and operates at 5 GHz with acceptable transmission characteristics. It should be noted that the height of 1 mm is approximately two thirds that of current products designed for 1.7 GHz and operation and one fifth that of current products designed for 5 GHz operation. A drastic reduction in height has thus been achieved. From the viewpoint of integration in monolithic microwave integrated circuits (MMICs), however, a circulator with a coplanar waveguide (CPW) structure is attractive. The CPW structure has a signal line and a ground in the same plane. Therefore, the circulator with a CPW structure can be easily fabricated at low cost by using a lithography process. Wen and Bayard have reported that their two-port-type CPW circulator operating at 7 GHz needs an internal magnetic field of more than 170 kA/m and that the device width is as long as 20 mm[3), 4)]. Ogasawara reported that Y-junction circulators with CPW successfully operated at some frequencies. However, no detail of the circulators and their transmission characteristics were given in his paper[5)]. Since the abovementioned pioneering work, no significant progress in research on CPW circulators has been reported.

The purpose of this study is to propose a small circulator with a CPW structure and operation frequency in the C-band and to analyze its transmission characteristics, using a high-frequency electromagnetic field simulation based on a three-dimensional finite element method (3D FEM).

2. Structure of a circulator with a CPW

Currently, a microstrip line is used as a transmission line in most circulator products. Figure 1 shows a schematic illustration of a microstrip line and a CPW. The electric lines of force and magnetic lines of force are denoted by solid lines and broken lines, respectively. As shown in Fig. 1(a), in the microstrip line, a signal line (LINE) is placed above a ground (GND) plane. An electric field is strong in the space sandwiched between a

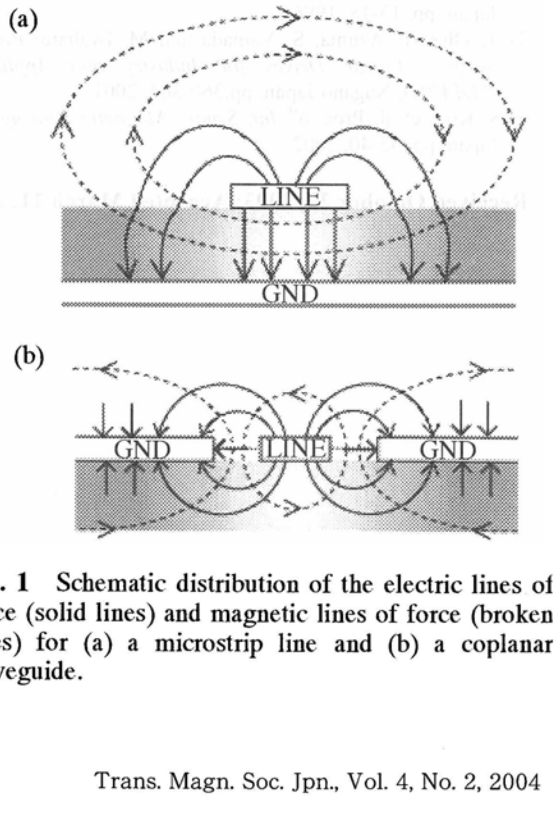


Fig. 1 Schematic distribution of the electric lines of force (solid lines) and magnetic lines of force (broken lines) for (a) a microstrip line and (b) a coplanar waveguide.

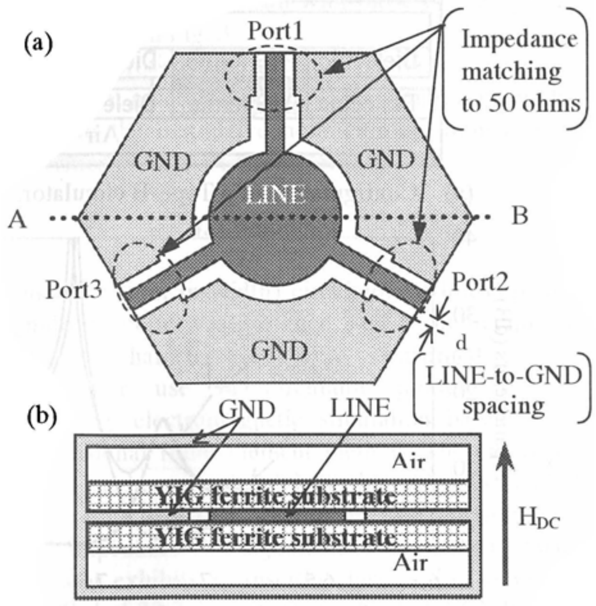


Fig. 2 Structure of a Type-A circulator with coplanar waveguide: (a) top view of the signal line and ground plane, and (b) cross-sectional view at line A-B.

LINE and a GND plane in a substrate. A CPW has a GND in an identical plane with a small separation between LINE and GND, as shown in Fig. 1(b). The electric field is strong at the fringe of a LINE[6].

Figure 2 shows the fundamental geometry of a circulator with a CPW structure proposed in this study. We call this a type-A circulator. The circulator has a Y-junction and three ports where impedance matching to 50 ohms was achieved, as shown in Fig. 2(a). A signal line and GND placed on a plane are sandwiched between two hexagonal YIG ferrite substrates and an air space, and the periphery of the Y-junction line is surrounded by GND areas, as shown in Fig. 2(b). The length of the diagonal of the hexagonal YIG ferrite substrate is 10 mm, smaller than that of previous device by Wen and Bayard[3), 4)]. A magnetic bias field (H_{DC}) is applied perpendicular to the YIG ferrite substrate.

High-frequency electromagnetic field simulation software based on Ansoft's 3D-FEM High-Frequency Structure Simulator (HFSS) Ver. 8.5 was used to analyze the transmission characteristics of the circulator with CPW. The physical parameters were set as follows: the YIG ferrite substrate has a relative dielectric constant (ε_r) of 15 (measured value in about 10 GHz), a saturation magnetization (Ms) of 90 mT ($4\pi Ms$ = 900 G), $\tan\delta$ of 0.0002 (measured value in about 9 GHz), and magnetic resonance width (ΔH) of 3.98 kA/m (50 Oe); the signal line has an electric conductivity (σ) of 6.1×10^7 S/m, assuming the value for Ag. We also assumed that an internal magnetic field (H_{DC}) of 64 kA/m (804 Oe) is uniformly applied to the YIG ferrite substrates. The LINE-to-GND spacing was strictly and carefully optimized to achieve impedance matching to 50 ohms.

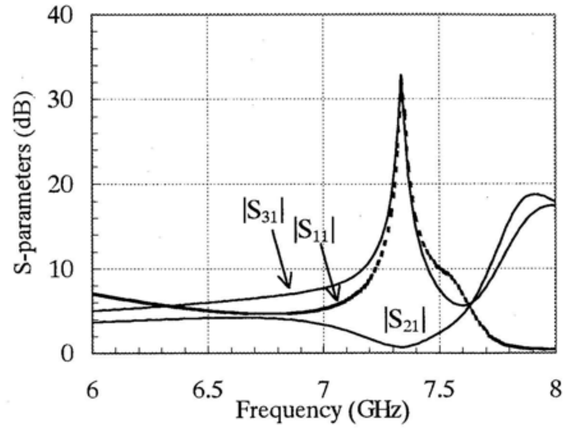


Fig. 3 Frequency characteristics of S-parameters for a Type-A circulator with CPW structure.

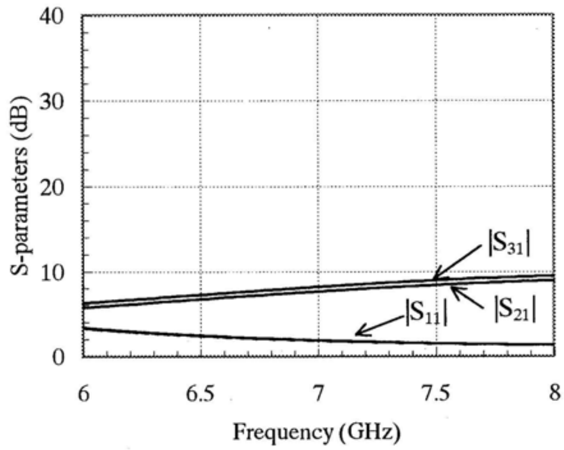


Fig. 4 Frequency characteristics of S-parameters for a circulator from which ground planes existing in the same plane as the Y-junction line had been removed (non-CPW circulator).

3. Results and Discussion

3.1 Non-reciprocal transmission characteristics

The characteristic impedance of a circuit is 50 ohms. Therefore, we designed a structure that adapts the method of adjusting the impedance between the lines, which is used in various designs, such as a resonator and a matching circuit, to the design of a circulator, and carries out a terminus to it by 50 ohms.

Figure 3 shows the frequency characteristics of the S-parameters for the Type-A circulator. Acceptable transmission characteristics for a practical circulator were obtained at 7.3 GHz; namely, insertion loss $|S_{21}|$ of 0.69 dB, isolation $|S_{31}|$ of 32.7 dB, return loss $|S_{11}|$ of 32.2 dB, and bandwidth of 77 MHz, which was defined as the band with $|S_{11}|$ of over 20 dB. To confirm that these nonreciprocal transmission characteristics are produced mainly by the CPW structure, the transmission characteristics and electric field distribution of a circulator from which GNDs which existed on the same plane as the Y-junction had been removed (we call this a non-CPW

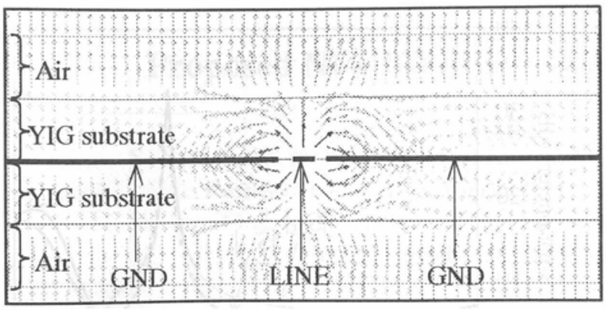


Fig. 5 Electric field distribution in a Type-A circulator with a coplanar waveguide at 7 GHz.

type circulator) were analyzed. As can be seen in Figure 4, which shows the frequency characteristics of the S-parameters for a non-CPW type circulator, a large proportion of input microwaves are reflected, and non-reciprocal transmission behavior cannot be obtained.

Figure 5 shows the distribution of the electric field for a circulator with a CPW (Type-A). As predicted from Fig. 1(b), a strong electric field exists in the space between LINE and GND. Precise observation of Fig. 5 proves that there is a wavy non-uniform distribution of the electric field in the GND plane sandwiched between the YIG ferrite substrates. In an ideal CPW operation, uniform distribution of the electric field should be observed, because a signal line and a GND on the identical plane are in equi-potential. The wavy non-uniform distribution of the electric field is probably due to the fact that the size of the GND electrode on the same plane as a Y-junction is larger than λ/4 (2.4 mm).

Thus, we confirmed that the CPW transmission mode was dominant in a circulator with a CPW (Type -A).

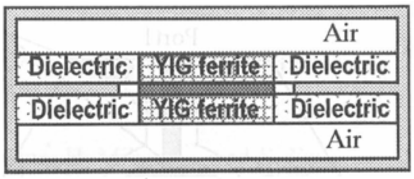
Based on this design, a circulator with a CPW (Type-A) was fabricated as a trial, and its nonreciprocal transmission characteristics (return loss of over 12 dB, isolation of 27 dB, and insertion loss of 5 dB at 7.9 GHz) were confirmed experimentally.

3.2 Origin of nonreciprocal transmission behavior

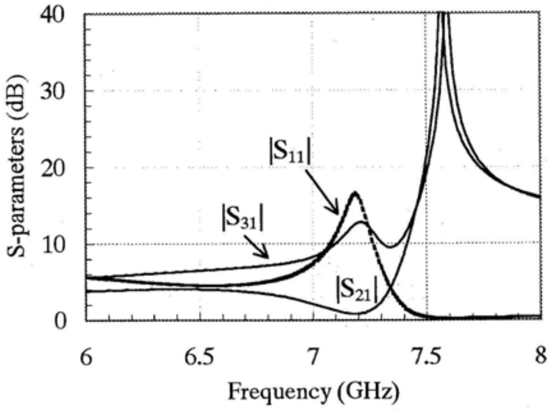
To verify the effect of YIG ferrite substrates on non-reciprocal transmission behavior, the transmission characteristics of circulators (Types B and C) from which YIG ferrite had been partially removed were simulated, and the results were compared with the results for the Type-A circulator.

In the Type-B circulator, two YIG ferrite disks with the same radius as the central circle of the Y-junction were placed just above and below central circle. Other areas surrounding the YIG ferrite disk were filled wih dielectric material, as shown in Fig. 6(a).

The Type-C circulator has a complementary geometry to the Type-B circulator with respect to the position of the YIG ferrite material and dielectric material, as shown in Fig. 7(a). As shown in Fig. 6(b) and 7(b), non-reciprocal transmission behavior was seen at 7.2 GHz in both circulators (Types B and C). The values of the insertion loss S_{21} and isolation S_{31}, however, were

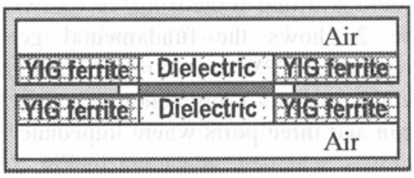


(a) Configuration of a Type-B circulator.

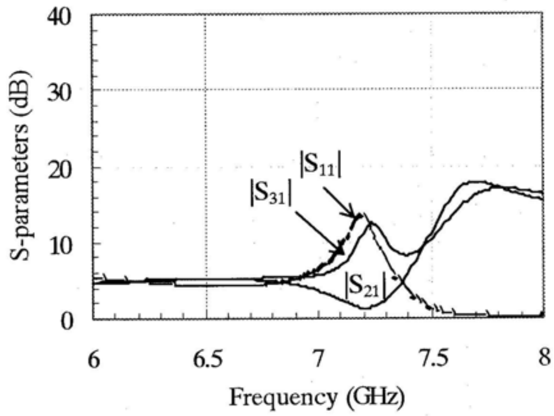


(b) Frequency characteristics of the S-parameters for a Type-B circulator.

Fig. 6 Circulator (Type-B) with YIG ferrite disks just above and below the central circle of the Y-junction. Areas outside the YIG ferrite disk are filled with dielectric plates.



(a) Configuration of a Type-C circulator.



(b) Frequency characteristics of the S-parameters for a Type-C circulator.

Fig. 7 Circulator (Type-C) with dielectric disks above and below the central circle of the Y-junction. Areas outside the dielectric disk are filled with YIG ferrite plates. The configurations of Type-B and Type-C circulators are complementary to each other with respect to the locations of the YIG ferrite and dielectric materials.

obviously small in comparison with those of the Type-A circulator shown in Fig. 3.

These results proved that all the YIG ferrite substrates covering the Y-junction with three coplanar waveguides contribute to the distinctive nonreciprocal transmission characteristics of Type-A circulators.

4. Conclusion

A small (10 mm in width) circulator with a coplanar waveguide structure was designed, and its nonreciprocal transmission characteristics were confirmed to be acceptable for use in circulator products by a high-frequency electromagnetic simulation based on a three-dimensional finite element method. The circulator consists of a hexagonal YIG ferrite substrate and a Y-junction with coplanar waveguide transmission lines where the impedance was adjusted to 50 ohms. At 7 GHz, the circulator exhibits an insertion loss $|S_{21}|$ of 0.69 dB, isolation $|S_{31}|$ of 32.7 dB, return loss $|S_{11}|$ of 32.2 dB, and bandwidth of 77 MHz. The nonreciprocal operation of the circulator is proved to be attributable to the wavy nonuniform distribution of the electric field in the YIG ferrite substrate.

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