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Design of Magnetic Circuit for Miniature Micro-strip Isolator Operating Above Resonance

T. Tanaka, H. J. Cha, K. Komada, K. Oshiro, H. Kurisu and S. Yamamoto
Faculty of Engineering, Yamaguchi University, Tokiwadai 2-16-1, Ube, 755-8611, Japan
Fax: 81-836-85-9621, e-mail: t-tanaka@yamaguchi-u.ac.jp

Configurations of a yoke and a permanent magnet was optimized in a down-sized micro-strip isolator which was achieved by utilizing a yttrium iron garnet ferrite single crystal with a very small full-width at half-maximum of ferromagnetic resonance curve. Combination of a 0.1-mm-thick iron yoke and a 0.1-mm-thick SmCo type permanent magnet could produce magnetic bias field of 500 Oe which enables the isolator to operate at 1.85 GHz in above resonance mode. The size of the designed isolator was 4×3.5×1 mm which was 1/90 of the conventional micro-strip isolator which operates in below resonance mode. Superior non-reciprocal transmission characteristics of the isolator were also proven by high frequency electromagnetic simulation based on a 3D finite-element-method.

Key words: micro-strip isolator, YIG ferrite, magnetic circuit, above resonance

1. INTRODUCTION

Electronic elements used in recent mobile devices are required to be miniaturized. An isolator, which is one of the electronic devises, gives non-reciprocal transmission of microwave utilizing gyro-magnetic effect in ferrite material. The isolator is, therefore, employed to protect the transistor in final stage in transmission circuit from the reflected wave, to ensure the high S/N communication, and to reduce electric power consumption.

The isolators are classified to lumped-element and distributed-element types. The lumped element type isolator is commonly used for cellular phones, because small size isolators are easily designed. The size of a world wide smallest lumped element type isolator for 2 GHz operation is 3.2 × 2.5 × 1.2 mm. However, further decrease in size, especially in height, encounters the limit because of its complex structure of transmission lines.

On the other hand, the distributed-element type isolator has advantages in integration and miniaturization because of the very simple structure of transmission line called as Y-junction. However, the horizontal size of the current distributed-element type isolator designed for use of cellular phone base station is 15 × 15 mm in 2 GHz operation. Drastic reduction in horizontal size of the isolator is necessary for the use in cellular phone. The current distributed-element type isolator was designed to operate in below resonance mode.

The authors already proposed that a distributed-element type micro-strip isolator operating in the vicinity of magnetic resonance in above resonance mode, and showed this type isolator is very easily miniaturized in its horizontal size, because difference in permeability for the circulating radio frequency magnetic field in clockwise and counterclockwise direction ($\mu_+ - \mu_-$) is large[1-2]. To achieve small insertion loss, yttrium iron garnet (YIG) ferrite single crystal with a very small ΔH, where ΔH is defined as full-width at half-maximum of ferromagnetic resonance curve was introduced in the isolator.

In author's previous work, experimental confirmation was carried out by applying a magnetic bias field from the outside of YIG ferrite platelet with a micro-strip transmission line. The isolator experimentally showed apparent non-reciprocal transmission characteristics with small insertion loss. To develop the isolator for the practical use, not only YIG ferrite and micro-strip line but also magnetic circuits composed of a permanent magnet and a magnetic yoke should be integrated in a case[3].

In this study, magnetic circuits were designed concerning the magnetic and dielectric properties of materials employed as a yoke and a permanent magnet using 3 dimensional finite element method for miniaturized micro-strip isolator. The transmission characteristics were also simulated for the designed magnetic circuits using high frequency electromagnetic structure simulator (HFSS Ansoft corp.).

2. DESIGN OF MAGNETIC CIRCUIT

2.1 Materials for yoke and permanent magnet

Magnetic bias fields (H_b) of 500 Oe must be applied to YIG ferrite single crystal in order to operate the isolator at 2 GHz band in proposed region. H_b in magnetic material is expressed by equation (1) in CGS unit[4-5].

$$H_b = H_{app} - N(4\pi M_S) \quad (1)$$

Here, H_{app}, N and M_S are the applied magnetic field, the demagnetization coefficient and the saturation magnetization for the ferrite magent, respectively. N is also expressed by equation (2).

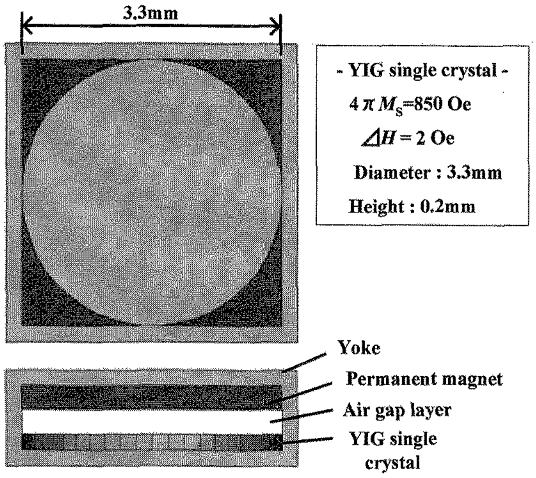


Fig. 1 Structure of the magnetic circuit.

$$N = 1 - \left[\frac{3}{2} \left\{ \frac{k^2}{\left(k^2-1\right)^{\frac{3}{2}}} \sin^{-1}\left(\frac{\sqrt{k^2-1}}{k} \right) - \frac{1}{k^2-1} \right\} \right] \quad (2)$$

k represents the ratio of diameter to thickness for ferrite disk.

In the case of 3.3-mm-diameter and 0.2-mm-thick platelet ferrite disk, N is estimated to be 0.87. This indicates that 1237 Oe of H_{app} is necessary to obtain 500 Oe of H_{b}. 1237 Oe of H_{app} is a relatively large to apply using mm size permanent magnet, and the permanent magnet also should possess electrical conductivity to work as GND line. This implies available permanent magnets are limited to be NdFeB type and SmCo type magnets.

SmCo magnet with the coecivity greater than 10 kOe, the remanent magnetic flux density of 1.15 T and the electrical conductivity greater than 10^6 S/m is assumed to be a permanent magnet in this study.

Configuration of a yoke is the most important to form a magnetic circuit, because the yoke must lead magnetic flux into ferrite magnet to obtain sufficient magnetic bias field. High relative permeability is, therefore, required for the yoke, and high electrical conductivity is also required, because the yoke must be GND line as well. In this study, iron is employed as the yoke. Magnetic and electrical properties for iron are 4000 of the relative permeability and 1.03×10^7S/m of the electrical conductivity.

2.2 Analysis of magnetic field distribution

One of the importances in design of magnetic circuit for micro-strip isolator is the size configuration of the yoke, the permanent magnet, and the ferrite magnet. The size of ferrite magnet is almost determined by the relationship between operation frequency and magnetic properties of the ferrite magnet. The size of YIG ferrite single crystal disk is set to 3.3 mm in diameter and 0.2 mm in thickness. Figure 1 indicates sample configuration for the calculation of magnetic fields and flux density distributions. Magnetic field distribution was calculated as a function of the yoke thickness by 3 dimensional finite element method. Strength of the magnetic field applied to YIG ferrite decreases with decreasing the yoke thickness as shown in Fig. 2. Although the yoke should be thin in order to miniaturize the isolator, the yoke tends to magnetically saturate for thinner yoke, and then the flux flows out of the yoke, resulting in weak magnetic bias fields. However, relatively strong magnetic fields comparable to required H_{app} are obtained for the designed isolator, even though the yoke thickness is as small as 0.1 mm, as shown in Fig. 2. The yoke thickness is, therefore, set to 0.1 mm.

Yoke should possess magnetically shielding effect. This means the yoke must be used under the unsaturated condition. Figure 3 shows the strength distributions of flux density for (a)

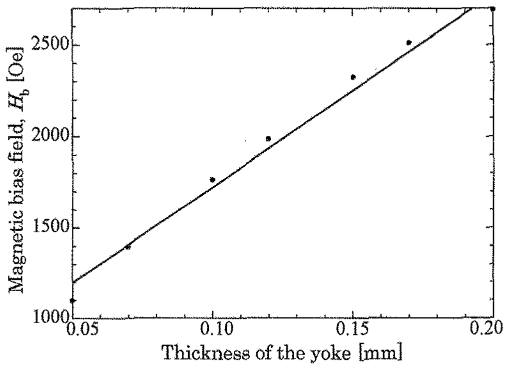
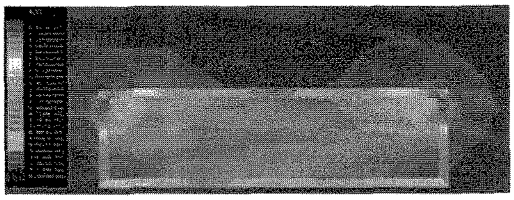
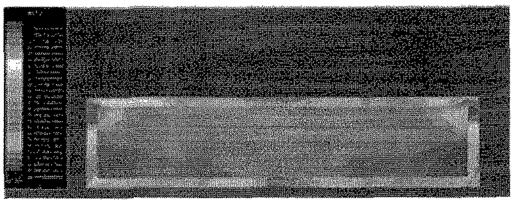


Fig. 2 Relationship between magnetic bias field in the center of YIG single crystal and thickness of the yoke obtained by calculation.



(a) 0.3-mm-thick permanent magnet



(b) 0.1-mm-thick permanent magnet

Fig. 3 Strength distribution of flux density.

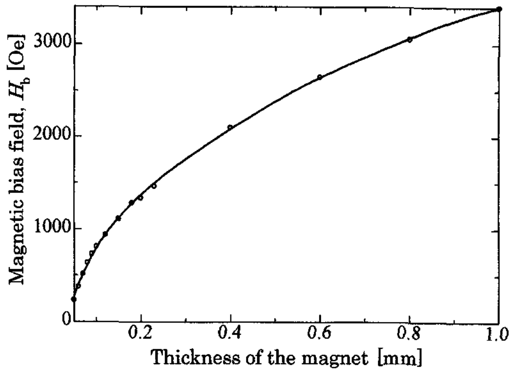


Fig. 4 Relationship between magnetic bias field in center of YIG single crystal and thickness of permanent magnet obtained by calculation.

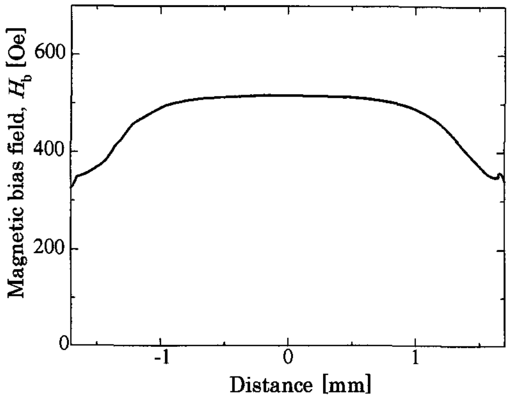


Fig. 5 Magnetic bias field distribution at the depth of 0.1 mm in YIG single crystal.

0.3-mm-thick and (b) 0.1-mm-thick permanent magnet. As shown in Fig. 3(a), the corners for the yoke with 0.3-mm-thick permanent magnet saturates, and the yoke may not work as shield. On the other hand, in the case of the 0.1-mm-thick permanent magnet, flux distributes only within the yoke because of unsaturated condition.

Figure 4 shows the relationship between magnetic bias field at the center of YIG ferrite and thickness for the permanent magnet. Magnetic bias fields increases with increase in the thickness of permanent magnet, and the flux density is calculated to excess the saturation flux density for the yoke above 0.2 mm in thickness. 500 Oe of H_b is obtained for the permanent magnet with 0.1 mm in thickness.

Figure 5 shows the magnetic bias field distribution at the depth of 0.1 mm in YIG ferrite. 0 in horizontal axis corresponds to the center of YIG ferrite. As shown in the figure, 500 Oe of uniform magnetic bias field is obtained in the range from −1 to 1 mm, which is located to the junction of transmission line.

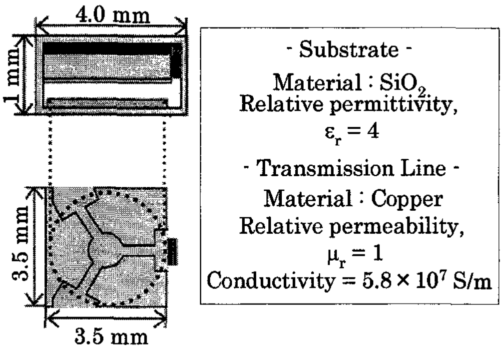


Fig. 6 Structure of micro-strip isolator.

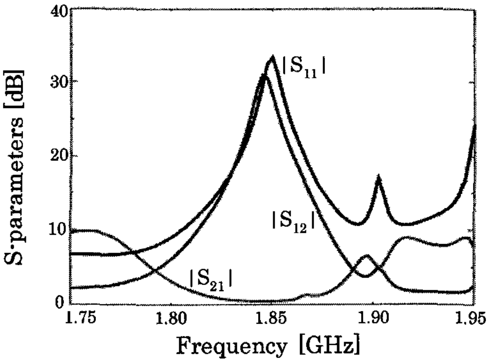


Fig. 7 Transmission characteristics for designed micro-strip isolator.

3. TRANSMISSION CHARACTERISTICS

Transmission characteristics were calculated for the designed isolator including the magnetic circuit and the permanent magnet. The thickness of the yoke and the permanent magnet are 0.1 mm and 0.1 mm, respectively. Figure 6 shows the structure of the isolator. Cu is assumed as a transmission line. SiO_2 with $\varepsilon_r = 4$ is employed for a dielectric substrate, and the thickness is 0.3 mm. The size of the element including chip resistance is 4×3.5×1 mm. Figure 7 shows calculated transmission characteristics. $|S_{11}|$, $|S_{12}|$, and $|S_{21}|$ represent the return loss, the isolation, and the insertion loss. Apparent non-reciprocal transmission characteristics were obtained at around 1.85 GHz. The isolation and insertion loss are 33 dB and 0.4 dB, which is sufficient transmission characteristics for the isolator.

4. CONCLUSION

To develop micro-strip isolator for practical use operating in above resonance mode, magnetic circuits were designed using 3D-FEM simulation. Combination of a 0.1-mm-thick iron yoke and a 0.1-mm-thick SmCo type permanent magnet could produce magnetic bias field of 500 Oe which enables the isolator to operate at about 2 GHz in above resonance mode. The size of the designed isolator was 4×3.5×1 mm. The volume of the isolator was 1/90 of that of the conventional micro-strip isolator which operates in below resonance mode. Superior non-reciprocal transmission characteristics, isolation of 33 dB and insertion loss of 0.4 dB 1.85 GHz, were proven for the isolator.

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