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Low Height YIG Circulator using Microstrip Line

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Circulators using microstrip line with a height of less than 1mm were designed and their operation was analyzed by using Finite-Element-Method. The circulator consists of $Y_3Fe_5O_{12}$ (YIG) ferrite plate, Ag Y-junction microstrip line, ferrite magnet and iron yoke. It was proved that (i) the uniform distribution of magnetic bias field more than 56 kA/m can be applied to YIG ferrite plate using a 0.25 mm thick YIG ferrite and a 0.25 mm thick ferrite magnet when the thickness of the iron yoke is more than 0.15 mm, (ii) the circulator with a height of 0.85 mm operates at 7 GHz with insertion loss less than 1 dB, isolation more than 20 dB and 200 MHz bandwidth at 20 dB (iii) in this type of circulator, operating frequency becomes lower with decreasing radius of the center circle of the Y-junction.
Key words: Microwave, circulator, microstrip line, Y-junction, YIG ferrite

1. INTRODUCTION

With increase of the demand of the miniaturization, reduction of height, and multi-functionalization of the mobile communication device such as the mobile phone and the wireless LAN, the demand of the miniaturization and the reduction in height of the electric elements used in the mobile communication device is increasing rapidly. Nowadays the height of most electric elements used in the mobile communication devices has been reduced to about 1 mm. However, the height of the electric elements using the magnetic material such as a circulator still remains more than 1.7 mm[1]. Therefore the reduction in height of the circulator is required immediately.

Circulator controls the transmission direction of microwave signal using the gyromagnetic effect. The circulator consists of transmission line, soft magnetic material (YIG ferrite), ferrite magnet producing magnetic bias field, and iron yoke is a part of magnetic circuit for magnetic bias field.

There are two crucial issues that disturb reduction in the height of a circulator. One is that lumped-element circulator which has a complex structure and consists of many parts such as capacitor and inductor has been used for the mobile communication devices.[2] The drastic miniaturization is difficult in this conventional structure. The other is decreasing magnetic bias field with height reduction. When thickness of hard magnetic material and iron yoke become thinner to reduce of the height of the circulator, it is feared that the magnetic bias field in a soft magnetic material probably become weaker.

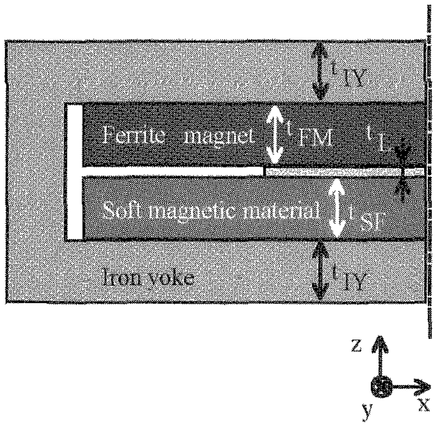
The purpose of this study is to prove the feasibility of the circulator with a height less than 1 mm using high frequency electromagnetic field simulation based on three dimensional finite element method. In our study, to reduce the device height, the circulator using microstrip line, which has a simpler structure than the lumped-element type was chosen. Also, in order to obtain a magnetic bias field required for non-reciprocal operation, ferrite material with a high tolerance demagnetizing field was selected, and a magnetic circuit which consists of ferrite magnet and iron yoke was carefully designed.

This paper is organized as follows. In Sec. 2, the low height circulator was designed by using microstrip line. In Sec. 3, analyzed results for the magnetic bias field which plays an important role for the operation of the circulator is shown. In Sec. 4, analyzed results for transmission characteristics of the designed circulator using the obtained magnetic field are described.

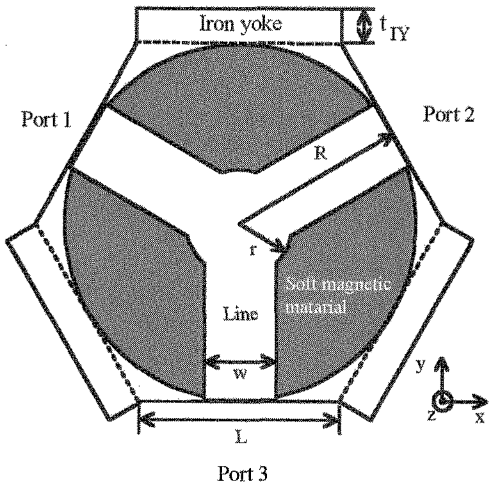
2. MODEL OF LOW HEIGHT CIRCULATOR

In order to realize the circulator with a height of less than 1 mm, we were cautious of the following three points, and the basic model for the circulator was set up. The three points are (i) The distance between line and ground cannot be made extremely small, since transmission loss of line and ground becomes larger with the smaller distance between line and ground, (ii) thickness of a yoke cannot be made extremely thin in order to secure of magnetic bias field, and (iii) since an demagnetizing field become larger when a hard magnetic material becomes thinner, the hard magnetic material cannot be made extremely thin.

In Fig. 1 the model of the low height circulator using microstrip line is shown. In order to separate a line as far as possible from the yoke which is play a role of ground, the line was located between the soft magnetic material and hard magnetic material, which are covered by iron yoke as shown in Fig. 1(a). Here we choose ferrite magnet which is insulator as the hard magnetic material. In Fig. 1 t_{FM}, t_{SF}, t_{IY}, and t_L are thickness of ferrite magnet, soft magnetic material, iron yoke, and transmission line, respectively. Thus the height of the circulator is given as $t_{FM}+t_{SF}+t_L+2t_{IY}$. We set the

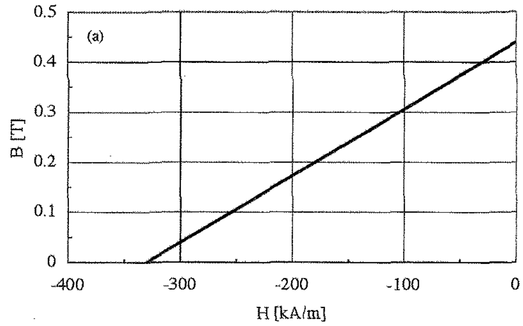


(a) A cross sectional view.

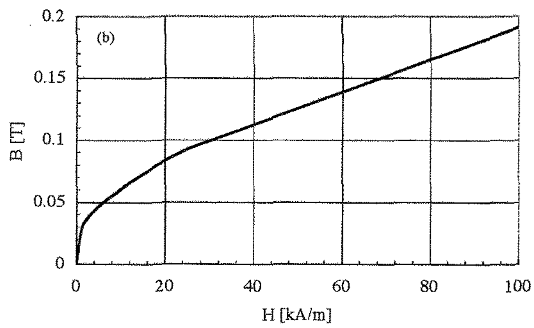


(b) Inplane view. Microstrip Y-junction, soft magnetic material platelet and iron yoke

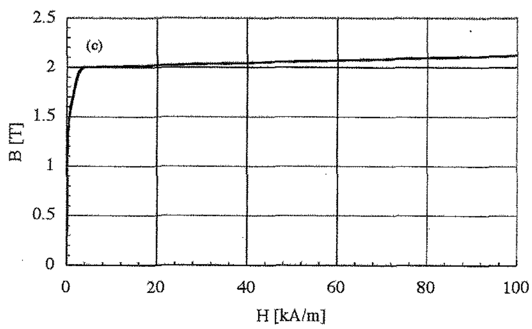
Fig. 1. The basic model of the low height circulator



(a) Demagnetizing B-H curve for ferrite magnet.



(b) initial curve for YIG ferrite



(c) initial curve for iron yoke

Fig. 2 B-H curves for materials used circulator.

thickness of the transmission line t_L at 10 μm.

The shapes of the ferrite magnet and the soft magnetic material are the cylindrical plate with a radius of R = 3.25 mm. As shown in Fig. 1(b), the microstrip Y-junction consist of three microstrip lines with a line width of w and center circle with a radius of r. The angle between each line is 120 degrees. The line width w and the radius of the center circle r are optimized by the numerical simulation.

The iron yoke consists of two hexagonal plates with a length of one side L = 3.75 mm (=2 $R/3^{1/2}$) and thickness of t_{IY} and three sidewalls of the thickness t_{IY} which connects an up-and-down hexagonal plates by the three sides.

3. RESULTS AND DISCUSSION

3.1 Magnetic bias field

In order to design a low height circulator with the structure of Fig. 1, it is necessary to know what magnetic field intensity can be induced in the soft magnetic material. The ferrite magnet YBM-9BE which has a large residual magnetic induction B_r = 0.44 T produced by Hitachi Metals Ltd. was chosen. As soft magnetic material, YIG ferrite which adjusted saturation magnetization Ms to 90 mT by containing additives was used. Henceforth, this YIG ferrite containing additives is expressed by YIG ferrite in this paper. A magnetostatic field analyzing software Maxwell 3D version 9 produced by Ansoft Corporation was used for numerical analysis of magnetic field. This software is based on Finite-Element-Method (FEM). B-H curves of the ferrite magnet, a YIG ferrite, and an iron yoke are shown in Fig. 2.

The dependence of the perpendicular (z-axis) component of a magnetic bias field H_z on thickness of YIG ferrite t_{SF} is shown in Fig. 3 for the fixed value of t_{FM} = 0.3 mm and t_{SF} = 0.2 mm. Bearing the condition of height of the circulator of less than 1 mm in mind, we set the range of thickness of YIG ferrite t_{SF} to from 0.2 mm to 0.3 mm. In Fig. 3 it is seen clearly that the strength of the magnetic bias field in YIG ferrite increases with the decrease of thickness of YIG ferrite t_{SF}. The YIG ferrite is acting as a gap of a magnetic

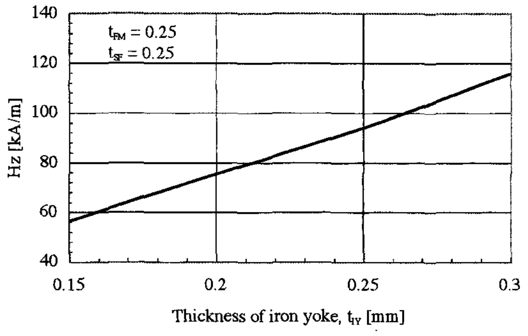


Fig. 5 The dependence of *z*-axis component of the magnetic bias field H_z on the thickness of the iron yoke t_{IY}.

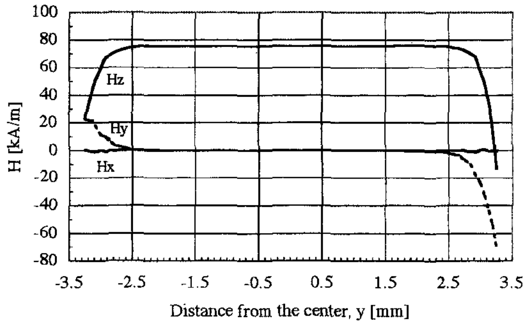


Fig. 6 The distribution of the magnetic bias field in YIG ferrite.

circuit which consists of ferrite magnet and iron yoke because the YIG ferrite becomes magnetic saturation completely by magnetic bias field. Therefore, with the decrease of thickness of YIG ferrite t_{SF} the permeance of the magnetic circuit increases and then the strength of the magnetic bias field in YIG ferrite increases. Figure 3 shows that *z*-axis component of magnetic bias field becomes about 82.4 kA/m (1030 Oe) when the thickness of YIG ferrite t_{SF} is 0.2 mm.

In Fig. 4 the dependence of *z*-axis component of the magnetic bias field H_z on the thickness of the ferrite magnet t_{FM} is shown for the fixed value of t_{SF} = 0.25 mm and t_{IY} = 0.2 mm. Contrary to the case of t_{SF} dependence, the magnetic bias field decreases with decreasing the thickness of ferrite magnet t_{FM}. This result can be explained that with the decrease of thickness of ferrite magnet t_{FM} the permeance of the magnetic circuit decreases because of demagnetizing field and then the strength of the magnetic bias field in YIG ferrite decreases.

We show the dependence of *z*-axis component of the magnetic bias field H_z on the thickness of the iron yoke t_{IY} in Fig. 5 for the fixed value of t_{FM} = 0.25 mm and t_{SF} = 0.25 mm. It is shown that the magnetic bias field decreases linearly with the decrease of the thickness of the iron yoke t_{IY}. This dependence appears because in the region of t_{IY} less than 0.3 mm iron yoke saturate magnetically the magnetic flux passing along the inside of the yoke is proportional to the cross-section area of the yoke. It is seen in Fig. 5 that with thickness of the iron yoke more than 0.15 mm we can obtain magnetic bias field more than 56 kA/m in YIG ferrite.

It was seen from Figs. 3-5 that the dependence of t_{IY}

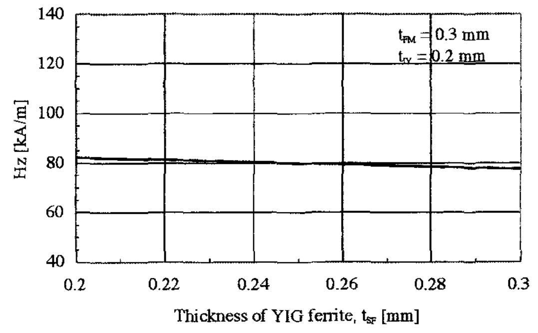


Fig. 3 The dependence of *z*-axis component of the magnetic bias field H_z on the thickness of the YIG ferrite t_{SF}.

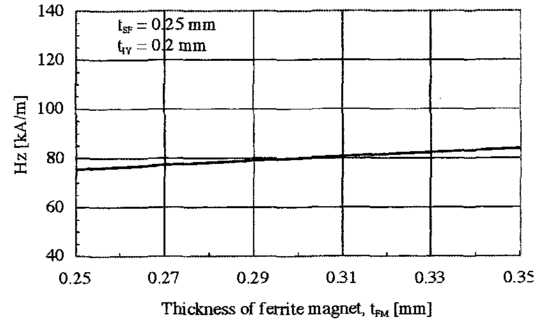


Fig. 4. The dependence of *z*-axis component of the magnetic bias field H_z on the thickness of the ferrite magnet t_{FM}.

is larger than the dependence of t_{SF} and t_{FM}. This means that the thickness of iron yoke t_{IY} plays an important role for the low height circulator from the viewpoint of reservation of a magnetic bias field.

Although we discussed only about the strength of *z*-axis component of the magnetic field in a YIG ferrite, a distribution of a magnetic field is important for circulator operation as well as the intensity of the magnetic field. The distribution of *x*-, *y*-, and *z*-axis components of magnetic bias field for y-axis are shown in Fig. 6. It is shown that a uniform magnetic bias field was obtained in almost all region of YIG ferrite. Although not shown here, we confirmed that the distribution of a magnetic field for *x*-axis and *z*-axis are uniform as well as for *y*-axis.

From the above discussion, using ferrite magnet YBM-9BE we can obtain a magnetic bias field of which strength become more than 56 kA/m when the thickness of iron yoke is more than 0.15 mm in YIG ferrite.

3.2 Transmission Characteristics

At first, transmission characteristics of the circulator with a line width w of 1.5 mm and a radius of the center circle of Y-junction r of 1 mm were calculated, changing strength of the magnetic bias field. We set the thickness of the YIG ferrite t_{SF} is 0.2 mm and the thickness of the ferrite magnet t_{FM} is 0.3 mm. We used physical parameters as follows: for YIG ferrite the relative dielectric constant ε = 15, the saturation magnetization M_s = 90 mT, $\tan\delta_\varepsilon$ = 0.0002, ΔH = 3.98 kA/m (50 Oe); for ferrite magnet the relative dielectric constant ε = 12,

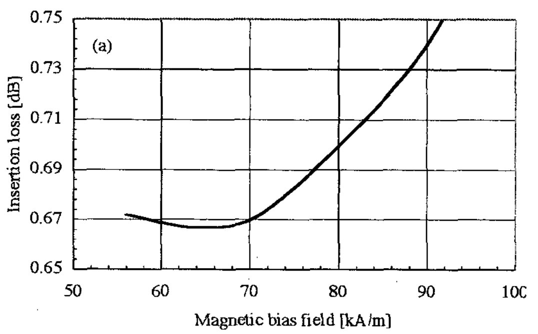


Fig. 7 The insertion loss as a function of the magnetic bias field in case of w = 1.5 mm, r = 1 mm, t_{FM} = 0.3 mm, and t_{SF} = 0.2 mm.

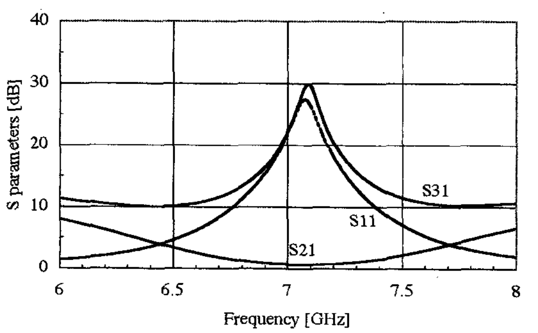


Fig. 8 S parameters as function of frequency with w = 1.5 mm, r = 1 mm t_{FM} = 0.3 mm, t_{SF} = 0.2 mm, and t_{IY} = 0.17 mm.

tanδ_ε = 0.02; for microstrip line the conductivity σ = 6.1x10^7 S/m which is the value for the Ag; for iron yoke the conductivity σ = 1.0x10^7 S/m. For this calculation, a high frequency electro magnetic wave analyzing software HFSS which is made by Ansoft Corporation was used. This software is based on FEM. The insertion loss S_{21} as a function of the magnetic bias field is shown in Fig. 7. It is clearly seen that the insertion loss S_{21} take minimum value when the strength of the magnetic bias field becomes about 64 kA/m (800 Oe).

The magnetic bias field of 64 kA/m can be obtained when the thickness of iron yoke is 0.17 mm (see Fig. 5). Then the total height of the circulator becomes 0.85 mm. The transmission characteristics are calculated with t_{IY} = 0.17 mm. The result is shown in Fig. 8. It is shown that this circulator operates about 7 GHz with 0.67 dB insertion loss, 30 dB isolation, 27 dB return loss, and about 200 MHz bandwidth at the 20 dB. Thus the possibility of low height circulator with height of 0.85 mm has been proved.

Finally, we mention the dependence of the operating frequency on the radius of the center circle of Y-junction r. The operating frequency as a function of the radius of the center circle of the Y-junction r is shown in Fig. 9 when the other parameters are fixed. It is clearly seen that with the decrease in the radius r the operating frequency becomes lower. That is, the circulator operates lower frequency with the smaller radius r when the size of x-y direction is fixed. Contrary, it is suggested that the size of the circulator can be miniaturized in x-y

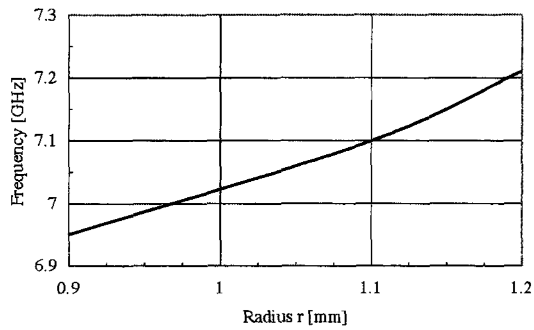


Fig. 9. The dependence of the operating frequency on the radius of center circle r.

directions by devising a pattern of the micostrip line when the operating frequency is fixed. This result has an important meaning for the possibility of a miniaturization of the circulator using the microstrip line.

4. Conclusion

The circulator with a height of 0.85 mm which is approximately a half height of current circulator products has been designed. Nonreciprocal operation has been confirmed at 7 GHz, with an insertion loss less than 1 dB, and an isolation and a return losses more than 20 dB, and 200 MHz bandwidth at the 20 dB. Thus the feasibility of a low height circulator with height of less than 1mm has been proved in this study.

Also, the possibility of miniaturization in x-y direction that the operating frequency becomes lower with the smaller radius of the center circle of the Y-junction was shown.

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