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High-Frequency Electromagnetic Simulation of an Extremely Low-Height Circulator Using a Microstrip Y-Junction

K. Oshiro, S. Yamamoto, T. Tanaka, H. Kurisu, M. Matsuura, H. Mikami*, S. Fujii*, and S. Murakami*
Faculty of Engineering, Yamaguchi University, *Ube, Yamaguchi 755-8611*
*Advanced Electronics Research Laboratory, Hitachi Metals, Ltd., *5200 Mikajiri, Kumagaya, 360-0843*

The transmission characteristics of a low-height circulator that we designed were simulated, using high-frequency electromagnetic analysis based on the finite element method. To reduce the height of the circulator, we dramatically reduced the thickness of the iron yoke and the ferrite magnet while maintaining the required magnetic bias field strength. The circulator has a hexagonal platelet shape with a diagonal line length of 7.5 mm and a height of 0.85 mm. It is composed of a 0.2-mm-thick ferrite magnet, a 0.3-mm-thick YIG ferrite platelet, a 0.17-mm-thick iron yoke, and a microstrip Y-junction. The simulation results exhibited acceptable nonreciprocal transmission characteristics with an insertion loss of 0.67 dB, and a return loss and an isolation both greater than 20 dB.

Key words: circulator, microwave, microstrip line, insertion loss, YIG ferrite

1. Introduction

The height and size of electronic devices used in mobile equipment must be decreased to meet the need for miniaturization and multi-functionalization of microwave communication systems such as cellular phones and wireless LANs. Although the height of most electronic devices has now been reduced to about 1 mm, that of circulators and isolators, which are nonreciprocal elements using the gyromagnetic effect of magnetic materials, is still more than 1.6 mm. It is necessary to design circulators operation in the low GHz range, because circulators operating in the C-band will become important components of applications such as wireless LANs and wireless connecting systems in the home.

Lumped-element circulators (LECs) are used in current mobile communication devices. However, it is difficult to achieve a drastic reduction in height of LECs, because they need many parts such as inductors and capacitors in order to provide the required electric properties, and consequently they have a complex structure. Another reason is that LECs cannot easily operate at frequencies above 2 GHz[1], because all of their components should be sufficiently small in relation to a quarter of a wavelength.

Many researchers have studied the transmission characteristics of distributed-element circulators using stripline Y-junctions (SL-YJCs) since Bosma's work in the 1960s[2-3]. Although much effort has been devoted to increasing the bandwidth[4-6], there are few reports of successful miniaturization of SL-YJCs. These are composed of only a few parts and have a simple structure. They are also suitable for operation at high frequencies in the S-, C-, and X-bands[1]. Since a circulator with a microstrip line Y-junction (MSL-YJC) has an advantage over an LEC in terms of reduced height, we focused on the former with the aim of realizing a low-height circulator.

The magnetic bias field plays an important role in nonreciprocal operation. A uniform and optimal magnetic bias field needs to be applied to soft magnetic material; thus, it is essential to optimize the magnetic circuit for the magnetic bias field. Unfortunately, few studies of circulators have discussed such optimization.

In this study, an extremely low-height MSL-YJC including a magnetic circuit for the magnetic bias field was designed using high-frequency electromagnetic simulation.

2. Design of a low-height circulator

2. 1 Circulator model

The structure of our low-height MSL-YJC[1] is shown in Fig. 1. The circulator has a hexagonal shape and consists of a soft magnetic ferrite platelet, a Y-junction transmission line, and a magnetic circuit composed of a ferrite magnet and an iron yoke. Doped yttrium iron garnet (YIG) ferrite with a saturation magnetization of 90 mT is considered as a soft magnetic material. A ferrite magnet and an iron yoke are used to apply magnetic bias fields to the YIG ferrite platelet. The iron yoke, whose thickness is denoted as t_{Yoke}, has three windows for ports in its side wall. The thickness of the ferrite magnet platelet and the YIG ferrite platelet are t_{MAG} and t_{YIG}, respectively. The Y-junction transmission line is constituted by a central circle of radius r and a microstrip line with line width 1.5 mm (see Fig. 1(c)). As shown in Fig. 1(d), the Y-junction transmission line is sandwiched by the ferrite magnet platelet and a YIG ferrite platelet in order to separate it from the yoke, which is electrically grounded. The thickness of the line is 10 μm. Assuming that t_{Yoke}, t_{MAG}, and t_{YIG} are each 0.25 mm, the total height of the circulator is 1.01 mm. This means that for a circulator with a total height of less than 1 mm, t_{Yoke}, t_{MAG}, and t_{YIG} need to be reduced to less than 0.25 mm each. In designing a low-height circulator, careful optimization of t_{Yoke}, t_{MAG}, and t_{YIG} is very important, because excessive reduction of the thickness of t_{Yoke} and t_{MAG} is likely to seriously reduce the magnetic bias field.

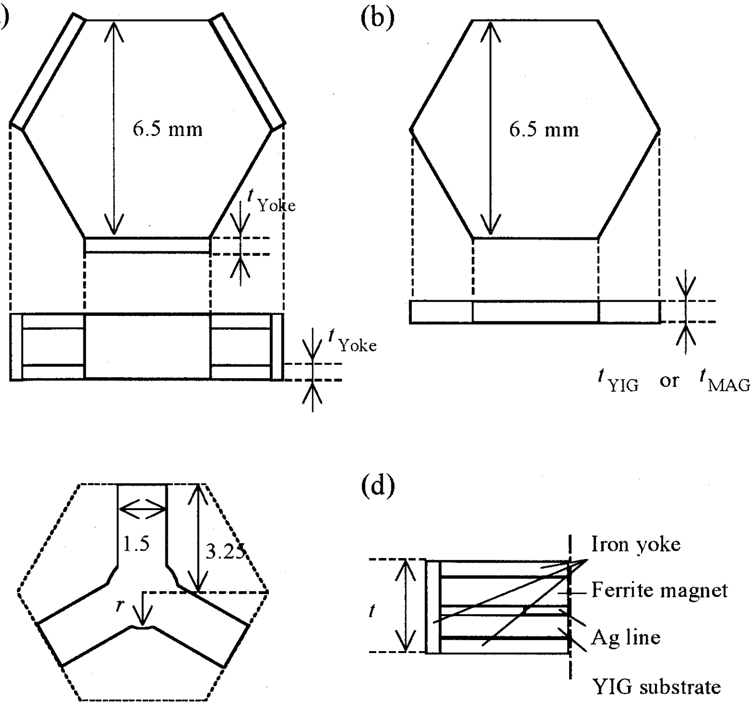


Fig. 1 Structure of the low-height circulator: (a) iron yoke. (b) ferrite magnet platelet or YIG ferrite platelet, (c) Ag microstrip Y-junction, and (d) cross-sectional structure of MSL-YJC.

2. 2 FEM analysis

The followings physical parameters were assumed: (1) for YIG ferrite, the dielectric constant ratio ε = 15 (typical value at 10 GHz), the saturation magnetization M_s = 90 mT, the loss tangent $\tan\delta_\varepsilon$ = 0.0002 (typical value at 9 GHz), and the FMR linewidth ΔH = 3.98 kA/m (typical value at 2 GHz), (2) for a ferrite magnet, ε = 12 (typical value at 10 GHz), $\tan\delta_\varepsilon$ = 0.02 (typical value at 9 GHz), (3) for a microstrip line of Ag, conductivity $\sigma = 6.1 \times 10^7$ S/m, and (4) for an iron yoke, $\sigma = 1.0 \times 10^7$ S/m. The transmission characteristics of the MSL-YJC were calculated by using a high-frequency electromagnetic analysis software tool, HFSS Ver. 8.5 (Ansoft Corporation), which is based on the three-dimensional finite element method (FEM). In this analysis the permeability tensor of soft ferrite is given as

$$\mu = \begin{pmatrix} \mu_r & -i\kappa_r & 0 \\ i\kappa_r & \mu_r & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

where

$$\mu_r = 1 + \frac{(\omega_b + i\alpha\omega)\omega_m}{(\omega_b + i\alpha\omega)^2 - \omega^2} \quad (2)$$

$$\kappa_r = \frac{\omega\omega_m}{(\omega_0 + i\alpha\omega)^2 - \omega^2} \quad (3)$$

and $\omega_b = \gamma H_b$, $\omega_m = \gamma M_s$, and $\alpha\omega = \gamma\Delta H/2$. Here, ω is the angular frequency, μ_0 is the permeability of vacuum, H_b is the magnetic bias field (internal field), and γ is the gyromagnetic ratio.

3. Results and Discussion

The transmission characteristics of the MLS-YJC, shown in Fig. 1, were simulated with r = 1 mm as a function of the magnetic bias field H_b. t_{YIG} and t_{MAG} were fixed at 0.2 mm and 0.3 mm, respectively. Since the circulator has a 120 degrees rotational symmetry around the z-axis, the values of S_{11}, S_{21}, and S_{31} are sufficient for a discussion of the transmission characteristics of this circulator. The dependence of the insertion loss on the magnetic bias field is shown in Fig. 2. The insertion loss, S_{21}, reaches a minimum at H_b = 64 kA/m.

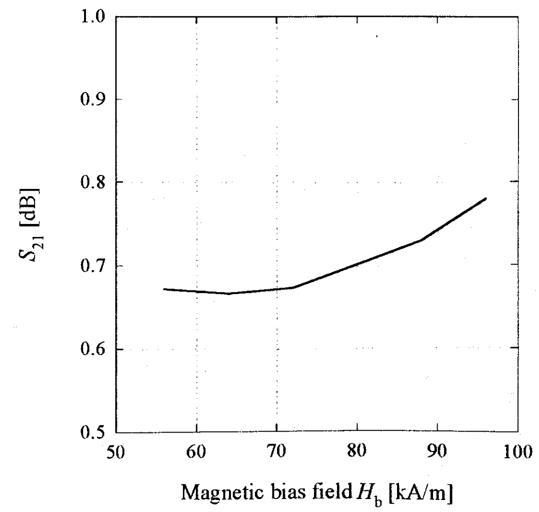
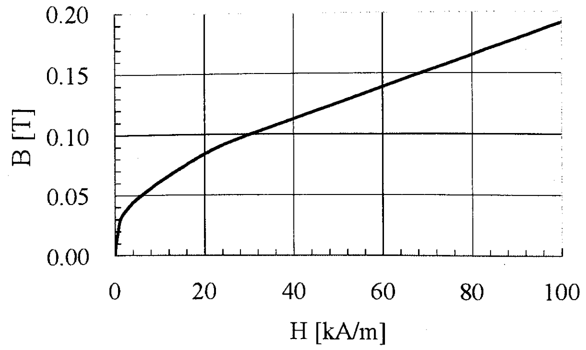
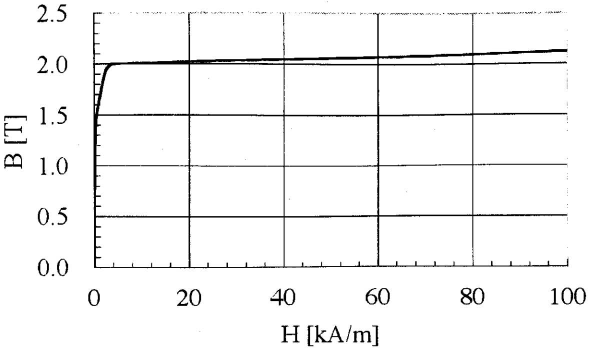


Fig. 2 Dependence of the insertion loss, S_{21}, on the magnetic bias field.



(a) YIG ferrite



(b) Iron

Fig. 3 Initial magnetization curves for (a) YIG ferrite and (b) iron.

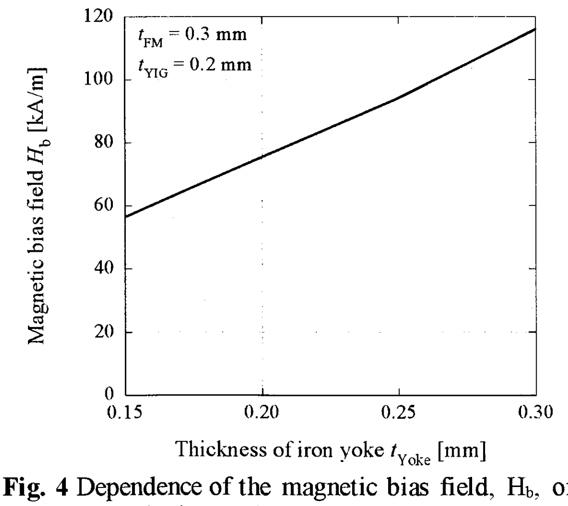


Fig. 4 Dependence of the magnetic bias field, H_b, on the thickness of the iron yoke.

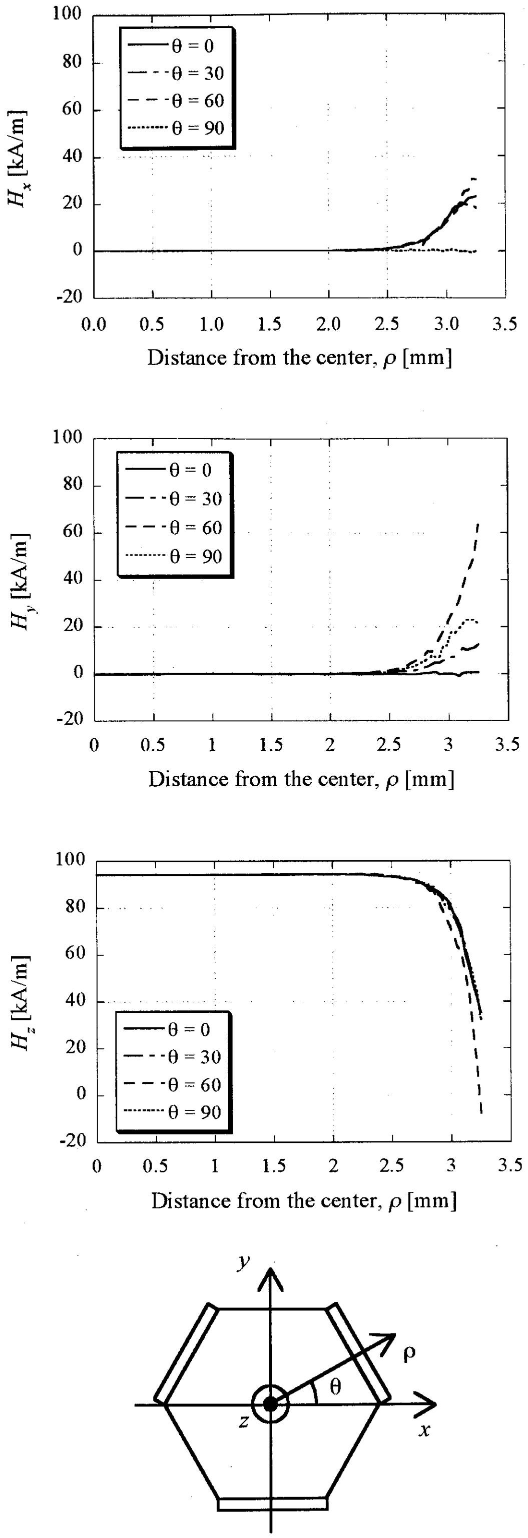


Fig. 5 Distribution of the magnetic bias field in a YIG ferrite platelet with t_{Yoke} = 0.17 mm.

To optimize the magnetic circuit, the dependence on t_{Yoke} of the magnetic bias field applied to the YIG ferrite platelet was analyzed. The ferrite magnet YBM-9BE, produced by Hitachi Metals, Ltd., was assumed to have residual magnetic induction B_r = 0.44 T and coercive force H_c = 340 kA/m in this analysis. A static magnetic field analysis "ferrite option" of HFSS was used in our numerical analysis of the magnetic bias fields. The B-H curves of the YIG ferrite and an iron yoke are shown in Fig. 3. The magnetic bias field increases linearly with increasing t_{Yoke} as shown in Fig. 4. When t_{Yoke} = 0.3 mm, magnetic bias field of about 110 kA/m is obtained. An optimum magnetic field of 64 kA/m at which gives minimum insertion loss is obtained when t_{Yoke} = 0.17 mm.

Distribution of the magnetic bias field in x, y, and z-directions with ρ as a parameter are shown in Fig. 5. The

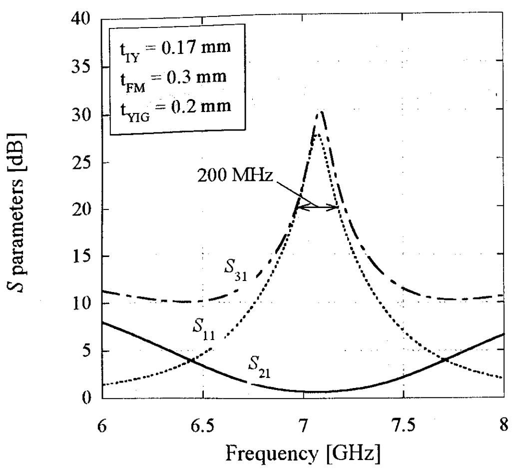


Fig. 6 Transmission characteristics of a 0.85-mm-height MSL-YJC.

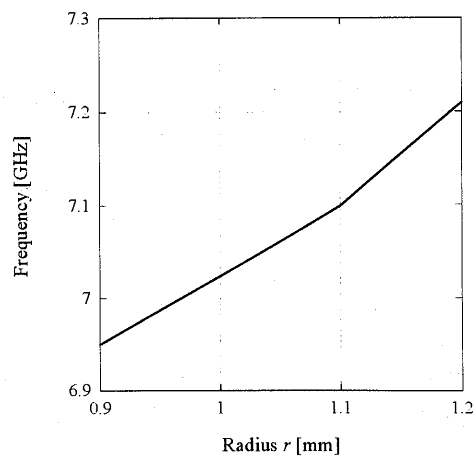


Fig. 7 Operation frequency as a function of the radius of the central circle in the Y-junction.

magnetic fields for x and y-direction are almost 0 up to ρ = 2.5 mm, and 64 kA/m of z-direction retains up to ρ = 2.5 mm from the center. In this situation, the physical configuration of t_{MAG} = 0.3 mm, t_{YIG} = 0.2 mm, and t_{Yoke} = 0.17 mm corresponds to 0.85 mm in total height. This height is approximately two thirds of that of the current circulator product, which is the lowest one and is operating at 1.95 GHz.

The transmission characteristics of an MSL-YJC with a height of 0.85 mm were simulated, using the results of static magnetic analysis, and are shown in Fig. 6. A small insertion loss, S_{21} = 0.67 dB, a large isolation, S_{31} = 30 dB, a large return loss, S_{11} = 27 dB, and a 200-MHz bandwidth at 20 dB were obtained at 7 GHz. This transmission characteristic is acceptable for actual circulator applications, although the insertion loss is slightly higher than that of circulators currently on the market, whose typical insertion loss is 0.4 to 0.6 dB.

Dependence of the operation frequency at which nonreciprocal transmission characteristics were observed in simulated results on the value of r for the Y-junction is shown in Fig. 7, where the other parameters are fixed. The operation frequency increases with increasing radius r of the central circle in the Y-junction. This can be explained as follows: when the radius r increases, the microstrip line (the straight part) of the Y-junction becomes shorter, and impedance matching is established at a higher frequency under the constrained size in the x-y plane. In other words, it is suggested that the size of the circulator can be reduced in the x-y plane by decreasing the radius r, when the operation frequency is fixed. This implies that miniaturization of MSL-YJC is possible at high operation frequencies.

On the basis of the simulation results described above, a MSL-YJC with a height of 1 mm and an operating frequency of 5 GHz was designed and fabricated in a trial[7]. The transmission characteristics of the fabricated circulator were almost identical to the results obtained by computer simulation.

4. Conclusion

A 0.85-mm-high circulator, whose height is approximately two thirds of the current lowest circulator products (this circulator operate at 1.95 GHz), was successfully designed. The circulator has a hexagonal platelet shape with a diagonal line length of 7.5 mm and a height of 0.85 mm, and is composed of a 0.2-mm-thick ferrite magnet, a 0.3-mm-thick YIG ferrite platelet, a 0.17-mm-thick iron yoke, and a microstrip Y-junction. The simulation results exhibited acceptable nonreciprocal transmission characteristics with an insertion loss of 0.67 dB, and a return loss and isolation both greater than 20 dB.

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