Microstrip Line on the Oppositely Magnetized Ferrite Substrate and Its Application to the Nonreciprocal Devices

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Abstract **— This paper newly proposes a microstrip line on the oppositely magnetized ferrite substrate. Strong nonreciprocal transmission characteristic was confirmed with both theory and experiments. After discussions of physical meaning of nonreciprocity of the line, a nonreciprocal four port junction and new design of a ring circulator along singular point of the bias field were demonstrated as applications of the strip line proposed.**

I. INTRODUCTION

Recently we have reported the nonreciprocal behavior of the hollow ferrite waveguide which consists of the microstrip line on the slot between oppositely magnetized ferrite substrates[1],[2]. In this paper, the hollow ferrite waveguide is extended to a microstrip line on the oppositely magnetized ferrite substrate, and the strong nonreciprocal behavior is discussed with that of the simple dispersion curve. A four port junction and a ring circulator are introduced as related applications of the microstrip line.

II. THEORY

The geometry of the hollow ferrite waveguide is shown in Fig.1 which has a slot s between oppositely magnetized ferrite slabs by the applied dc magnetic field H_0[1],[2]. The dispersion relation of the waveguide is easily derived from Maxwell's equation with magnetic wall boundary condition under the approximation of independent of the field to the magnetic field direction($\partial/\partial z = 0$)[2].

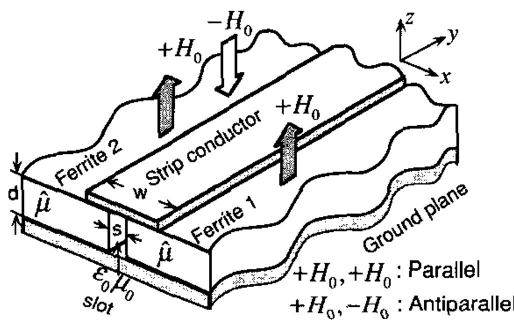

Fig.1 Geometry of the hollow ferrite waveguide.

$$\tanh k_{x3}s = -k_{x3}\left\{L_2M_1\left(1-e^{-2k_{x1}t}\right)\left(1+O_2e^{-2k_{x2}t}\right) + L_1N_2\left(1-e^{-2k_{x2}t}\right)\left(1+O_1e^{-2k_{x1}t}\right)\right\}$$
$$\times\left\{k_{x3}^2L_1L_2\left(1+O_1e^{-2k_{x1}t}\right)\left(1+O_2e^{-2k_{x2}t}\right) + M_1N_2\left(1-e^{-2k_{x1}t}\right)\left(1-e^{-2k_{x2}t}\right)\right\}^{-1} \quad (1)$$

where

$$k_{xn}^2 = \beta^2 - \omega^2\mu_0\mu_{\mathrm{eff}n}\varepsilon,\ k_{x3}^2 = \beta^2 - \omega^2\mu_0\varepsilon_0,$$
$$L_n = \mu_n^2 - \kappa_n^2,$$
$$M_n = \mu_n k_{xn} + \kappa_n\beta,\ N_n = \mu_n k_{xn} - \kappa_n\beta,$$
$$O_1 = M_1/N_1,\ O_2 = N_2/M_2,$$
$$t = (w - s)/2,\ n = 1, 2.$$

In such a two dimensional approximation, dominant E_z, H_x and H_y, (E^z) mode can propagate separately with H_z, E_x and E_y, (H^z) mode in the line.

The dispersion curves of the hollow ferrite waveguide calculate from Eq.(1) are shown in Fig.2 for the same dc magnetic field direction. In this case the dispersion diagrams are symmetry and nonreciprocal phenomenon does not appear but new electromagnetic surface (MSSW) mode in

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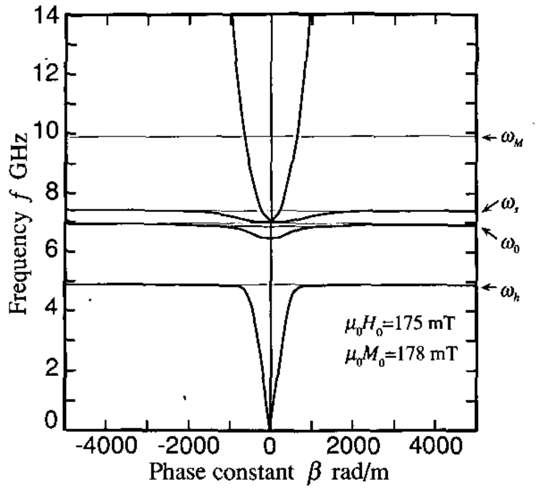
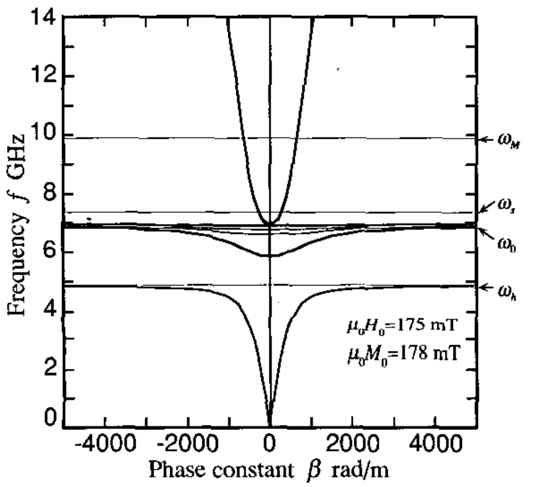
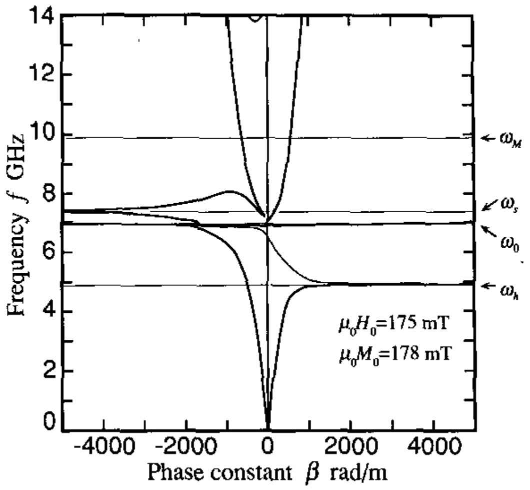


(a) $s = 1$ mm, $w = 3$ mm.

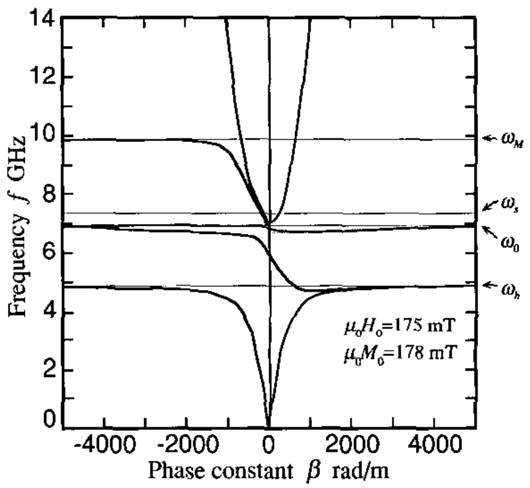


(b) $s = 0$ mm, $w = 3$ mm.

Fig.2 Dispersion curves of the microstrip line as a function of the width of the slot for the same magnetic field direction.



(a) $s = 1$ mm, $w = 3$ mm.



(b) $s = 0$ mm, $w = 3$ mm.

Fig.3 Dispersion curves of the microstrip line as a function of the width of the slot for the oppositely magnetized substrates.

between $\omega_0 = \gamma\mu_0\sqrt{H_0(H_0 + M_0)}$ and $\omega_s = \gamma\mu_0(H_0 + M_0/2)$ can propagate along the slot[3]. Where γ is the gyromagnetic ratio, H_0 and M_0 are internal magnetic field and saturation magnetization of the ferrite respectively. When applied dc magnetic field is taken to be the same direction and without air gap, it coincides with the dispersion relation of the edge guide mode discussed by M.E.Hines [4].

The dispersion curves of the hollow ferrite waveguide for the oppositely magnetized ferrite substrate are shown in Fig.3 as a function of the width of the slot s. It can be seen from the figure the nonreciprocal characteristic can be found around gyromagnetic frequencies of $\omega_h = \gamma\mu_0 H_0$ and ω_0 due to the difference between forward and backward dispersion curves. When s approaches to zero, dispersion curve around gyromagnetic frequency is spread out to $\omega_M = \gamma\mu_0(H_0 + M_0)$ with wide cutoff frequency. Therefore, nonreciprocal characteristic will be improved.

III. Experiment

To confirm the nonreciprocal characteristic of the microstrip line on the oppositely magnetized ferrite substrate without the slot, experiment on the waveguide was carried out using a polycrystalline yttrium iron garnet (YIG) slab of dimension of 10mm × 30mm in thickness 1mm with the saturation magnetization of $\mu_0 M_0$=155 mT. The geometry of the experiment is shown in Fig4. Two permanent magnets having dimension of 30mm×12mm×7mm with maximum magnetic field of 420 mT were arranged under the microstrip line and it was oppositely magnetized as shown in the figure.

The experimental result is shown in Fig.5. Strong nonreciprocal behavior more than 40 dB was found with different characteristic between S_{12} and S_{21} at 9.8 GHz, but bandwidth of the nonreciprocity is relatively narrow.

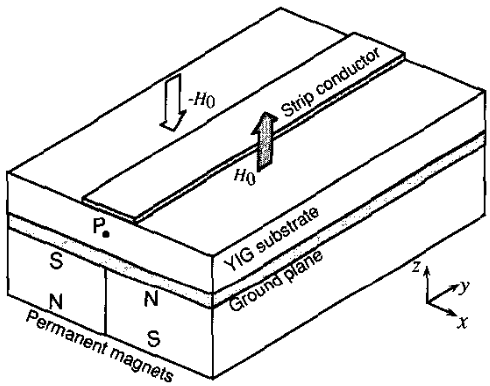


Fig.4 Geometry of the experimental setup.

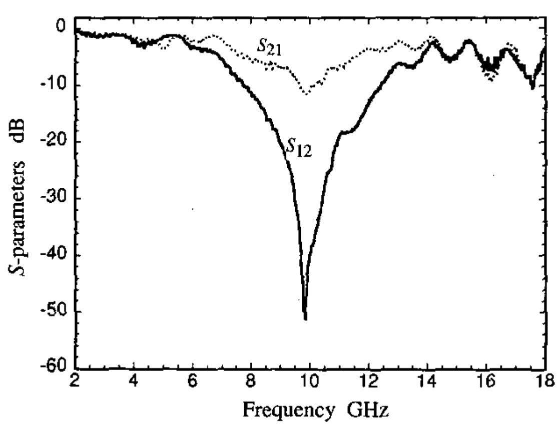


Fig.5 Nonreciprocal transmission characteristic of the microstrip line on the oppositely magnetized ferrite substrate.

IV. Discussions

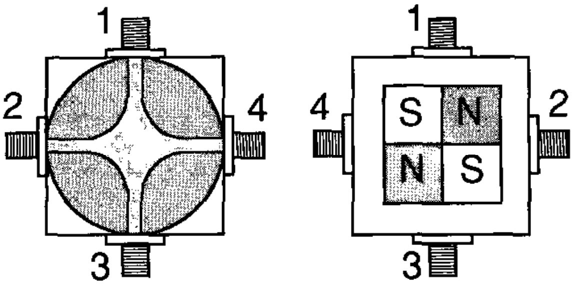
The mechanism of the strong nonreciprocity of the line is discussed. One reason is the direction of rotation of the spin motion which is discussed in the magnetostatic surface wave mode[3],[5]. Another reason is the large propagation constant around gyromagnetic frequencies of ω_h and ω_M which shows the lossy characteristic due to the small wavelength in the line.

Furthermore, behavior of the electromagnetic field is very interesting at singular point of the bias field distribution of P as pointed in Fig.4, where the direction of the magnetic field in the z direction changes abruptly through zero magnetic field. Although profile of the magnetic field at P changes with the geometry of the permanent magnets, there is a strong transverse component of the dc magnetic field in x direction. Transverse component of the dc magnetic field may not affect on the E^z mode but affect on the E_x, H_y, H_z, (E^x) mode which is dominant mode for transverse magnetic field[6]. However, E^x mode is under cutoff because of the thin ferrite substrate in the microstrip line. On the other hand, E^z mode is also under cutoff in the low magnetic field near the singular point P for the forward wave propagation , but backward wave concentrates at the edges of the microstrip line and cutoff behavior does not appear because of the nonzero magnetic field region at strip edges. Singular point may be equivalent behaviors as the slot. Therefore, strong nonreciprocal characteristic in the microstrip line is attributed without additional lossy material[4].

V. Application to a Four Port Junction and a Circulator

Two applications of the microstrip line are proposed and demonstrated. One is a nonreciprocal four port junction as shown in Fig.6. It consists of a cross microstrip line on a ferrite disk having diameter of 32 mm with thickness of 1 mm magnetized alternately using four permanent magnets. Fig.7 shows experimental result. Nonreciprocal behavior are observed between port 1 and 2. The propagation directions are reversed when the magnets are rotated 90 degree. The reciprocal characteristics are observed between port 1 and 3.

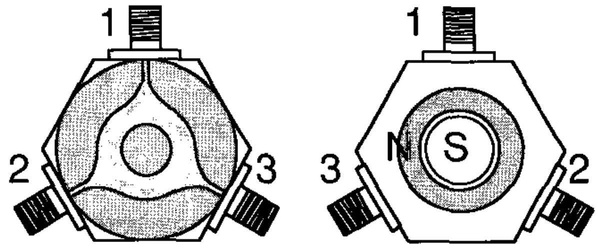
Another interesting device of the line is a new design of a circulator as shown in Fig.8. A ferrite disk having diameter of 32 mm with thickness of 1 mm is magnetized oppositely using two concentric circular permanent magnets having opposite sign with 1 mm airgap. A circular microstrip line is fabricated on the ferrite disk to guide the wave along the singular region of the bias field distribution. Measured



(a) Top view.

(b) Bottom view with 4 permanent magnets (10mm×10mm×10mm).

Fig.6 Design of the nonreciprocal four port junction.



(a) Top view.

(b) Bottom view with two circular permanent magnets with airgap.

Fig.8 Design of the ring circulator to guide wave along a airgap of magnetic poles.

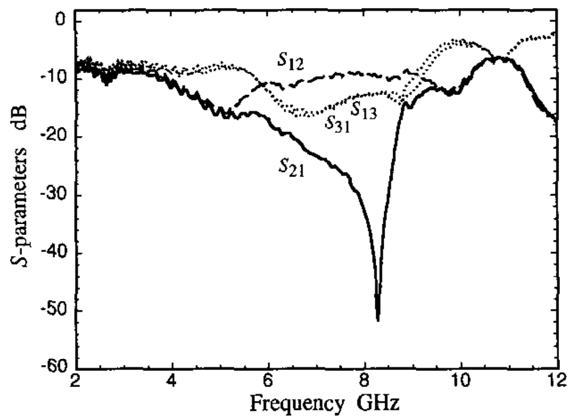


Fig.7 Experimental result of the four port junction.

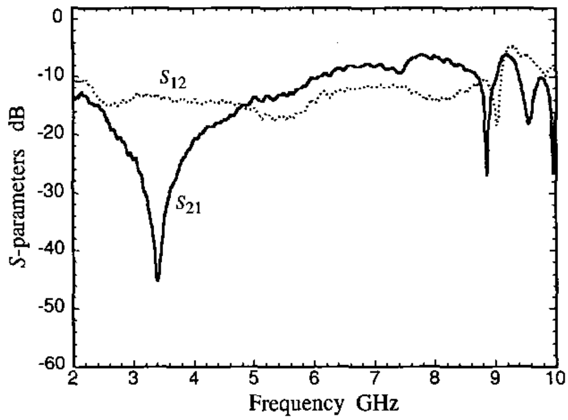


Fig.9 Experimental result of the ring circulator.

characteristic of the circulator is shown in Fig.9, which is relative band width 5.9% at 3.5 GHz.

VI. CONCLUSION

We have discussed the nonreciprocal characteristics of the microstrip line on the oppositely magnetized ferrite substrate both theoretically and experimentally. The narrow band width of the nonreciprocity and the insertion loss of the proposed microstrip line are pointed out as problems. They would be further developed by a careful design of the magnetic poles and geometry of the strip conductor.

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