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FABRICATION AND MEASUREMENT OF A COPLANAR CIRCULATOR WITH 65 μm YIG THIN FILM

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Abstract—A circulator with a coplanar structure is designed and analysed using a three dimensional finite element method. Based on the proposed design, the circulator is fabricated with a YIG (Yttrium Iron Garnet). The thickness of YIG is only 65 μm. The design is planar and realized by stacking several layers, resulting in a potentially simple and low cost industrial process. Simulated results are better than measured ones but circulation is obtained around 9 GHz. Measured insertion loss is 5 dB and isolation is 36 dB giving interesting perspectives for the device.

1. INTRODUCTION

Works on electronic devices used in mobile telecommunications have a general objective to reduce the size of components and of course to reduce the cost of fabrication. In the field of wireless systems, the circulator represents an important part. Generally the circulators are using ferrite materials and the fabrication is done one by one.

In this paper, we present a coplanar circulator extrapolated from the stripline circulator studied by Bosma [1]. The device with coplanar structure is well matched to microwave integrated circuits because the signal line and the ground are located in the same plane, so it will be easy to interconnect with other components. Moreover, the design that we propose, allows fabrication using standard lift-off process and collective fabrication also. All of this results in the minimization of the cost of the final components. Some time ago, Ogasawara first reported

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a coplanar waveguide circulator on a ferrite substrate. However, no details on the circulator and its transmission characteristics were given in his paper [2]. Koshiji et al. [3] have designed a coplanar waveguide with a big cylindrical ferrite post. In 2004–2005, Oshiro et al. [4] realized and measured a coplanar circulator using two substrates of YIG (thickness of each post is 500 µm). In previous papers, a new coplanar circulator with the CPW structure based on YIG film was proposed and its transmission characteristics were analyzed using a three-dimensional (3D) finite element method (FEM) [5, 6]. In this paper, a circulator based on the design studies in [5, 6] is fabricated with only 65 µm ferrite film and its transmission characteristics are measured by using three GSG coplanar probes are connected with a vector network analyzer.

2. STRATEGIES OF THE FUNCTION FREQUENCY

The operation of a non-reciprocal circulator with ferrite was described by Bosma [7] and analysed through simplified assumptions. The following specific physical parameters are used for our simulations: the YIG film is modelled with a dielectric constant $\varepsilon = 15.3$, a dielectric loss tangent with a maximum of $\tan\delta = 2 \cdot 10^{-4}$ (typical values at 8.3 GHz, given by the Temex company for massive ferrite film), a saturation magnetization $M_s = 0.139\,\mathrm{kA/m}$ and a ferromagnetic resonance (FMR) line width $\Delta H = 7.985$ kA/m. For a conductor line and GND planes made of copper, the conductivity is $\sigma = 58 \cdot 10^6\,\mathrm{S/m}$.

The ferrite is supposed to be saturated and the internal bias field is supposed to be uniform. In this analysis the permeability tensor for a soft ferrite is given by:

$$\bar{\bar{\mu}} = \mu_0 \begin{bmatrix} \mu & -jk & 0 \\ jk & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$\mu = \mu' - j\mu'' = 1 + \frac{(\omega_b + j\alpha\omega)\,\omega_m}{(\omega_b + j\alpha\omega)^2 - \omega^2} \tag{2}$$

$$\kappa = \kappa' - j\kappa'' = \frac{\omega\omega_m}{(\omega_b + j\alpha\omega)^2 - \omega^2} \tag{3}$$

where $\omega_b = \gamma H_i$ is the gyromagnetic resonance frequency, $\omega_m = \gamma M_s$ and $\alpha\omega = \gamma\Delta H/2$. Here ω is the angular frequency, H_i is the magnetic bias field (internal field), and γ is the gyromagnetic ratio. High frequency electromagnetic simulations are done using Ansoft HFSS. This software is based on the three dimensional finite elements method (FEM).

The real and imaginary parts of the permeability tensor are shown in Figure 1 for saturation magnetization of 0.139 kA/m and damping factor of 0.01. Figure 1 shows a frequency sweep with a fixed applied field. It also shows three different zones according to the frequency. The first zone concerns the resonant frequency. At this frequency μ and k present a resonant behavior. The two other zones (named "below resonance" and "above resonance") are the good frequency bands to design the central frequency circulator.

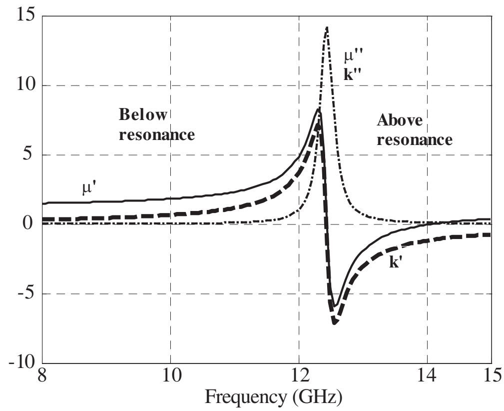

Figure 1. Ferromagnetic resonance: real and imaginary parts of the elements of the permeability tensor as a function of frequency sweep (557 kA/m applied field).

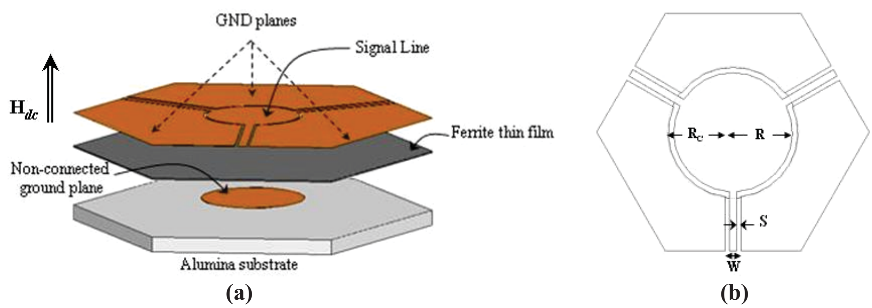

Figure 2. Structure of the coplanar circulator: (a) With the different stages (b) Top view with the different geometrical parameters.

3. DESIGN OF THE FERRITE COPLANAR CIRCULATOR

Figure 2 shows our proposed circulator with a coplanar structure. The circulator is composed of a Y-junction and three adapted ports (50 Ω). As seen on Figure 2(a), the signal line and the ground plane of the CPW are placed on an identical plane over the YIG film of thickness 65 µm (h_f). This magnetic film is placed over a 635 µm (h_{al}) of commercial alumina substrate (with the permittivity $\varepsilon_r = 9.2$ and the dielectric loss tangent $\tan\delta = 6 \cdot 10^{-4}$ which are values given by the Neyco company at 9.8 GHz). The lower non-connected ground plane is located between the ferrite and the dielectric substrate, its role is to facilitate the field transition between the line accesses and the centre of the 3 circulator [6]. Finally, a magnetic bias field ($H_{dc} = 477$ kA/m) is applied, perpendicular, to the YIG layer.

The simulation model of the circulator is shown in Figure 2(a). The geometry of the design is optimized using the HFSS software. The design frequency is 9 GHz. The dimensions (see Figure 2(b)) are set to:

- $R = 2$ mm (the radius of the central conductor "Signal Line"),
- $W = 400$ µm (the width of the Signal Line),
- $S = 130$ µm (space between GND plane and Signal Line),
- $R_c = 2.23$ mm (Radius of the non-connected ground plane),
- $h_f = 65$ µm and $h_{al} = 635$ µm.

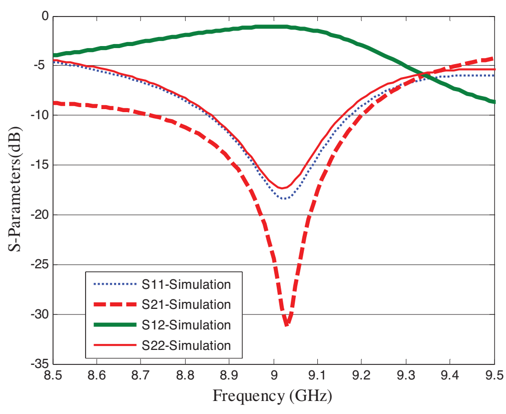

Figure 3. Simulation (Insertion loss, isolation and return loss) results of coplanar circulator with 65 µm ferrite thick film.

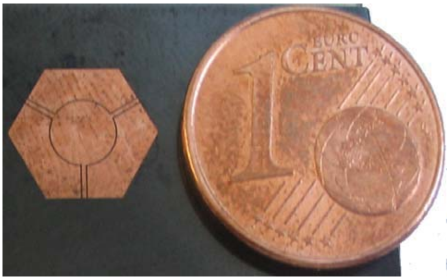

Figure 4. Prototype of the ferrite coplanar circulator.

Figure 5. Circulator under test using three probes system; two probes are connected to the VNA and the third one (central one) is connected to an adapted load.

The simulated S-parameters of the circulator are shown in Figure 3. Non-reciprocal transmission behaviour was found at 9 GHz. The insertion loss $|S_{12}|$ is less than 1 dB, the isolation $|S_{21}|$ is 31 dB, the return loss $|S_{11}|$ is 18 dB and the bandwidth (at 20 dB) is 110 MHz.

4. FABRICATION AND MEASUREMENTS

The 65 μm ferrite film is obtained by grinding a commercial ferrite slab. Polishing is done to finish the preparation of the film in order to reduce the roughness of the surface. Then, the 65 μm ferrite film is stuck on an alumina substrate with a thickness of 635 μm thick. The copper Signal Line and GND planes have a thickness of 4 μm. They are patterned on the YIG ferrite using lift-off process. One prototype with the design of Figure 2 is realized. A picture is shown on Figure 4.

The transmission characteristic of the circulator is measured using a vector network analyzer (VNA) associated to probe station. This measurement platform is equipped with 3 arms oriented at 120° from each other. The arms end with by a coplanar GSG probe. For the measurement characteristics of the circulator, one of the 3 branches is connected to a 50 Ω load (See Figure 5). For measurements, the magnetic bias field is realized using two permanent magnets placed above and below the device.

The measures of S-parameters are presented in Figure 6. As we can see, significant non-reciprocal transmission behaviour is found at 9.1 GHz. The insertion loss $|S_{12}|$ is about 5 dB, the isolation $|S_{21}|$ is 36 dB, the return loss $|S_{11}|$ is 10 dB and the bandwidth (at 20 dB) is

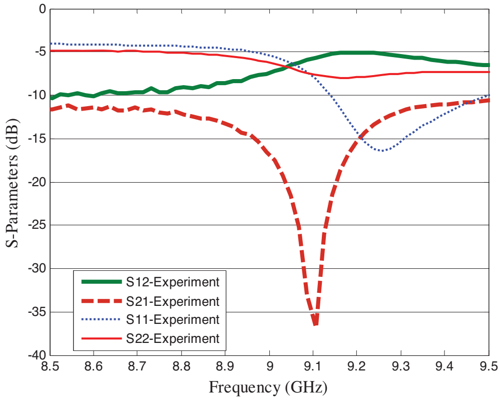

Figure 6. Experimental (Insertion loss, isolation and return loss) results of the coplanar circulator with 65 µm thick film.

115 MHz.

A small difference in the central frequency can be seen between the simulation (Figure 3) and the measurement (Figure 6). This is due to the fact that the biasing magnetic field is not as strong as in the simulation case. In measurement, reflection parameters S_{11} and S_{22} are not symmetric. This is due to problems during lift-off process. Finally, the geometry of line of port 2 was not exactly the same as the one of port 1. The measured value of the insertion loss ($|S_{12}| = 5$ dB) is bigger than the simulation one ($|S_{12}| = 1$ dB) for many reasons. Several parameters have influence on fabrication, the misalignment between the non-connected ground plane and the central conductor contributes to the losses. The roughness of ferrite layer gives, as a result, rough conductors. So, when the thickness of these layers decreases, losses are getting more sensitive to roughness [8, 9]. In spite of these remarks that are not really positive, the device operates like a circulator. This is already a good result since the size of the device is really compact.

5. CONCLUSIONS

A coplanar circulator has been designed and realized. This device has only required a ferrite YIG film of 65 µm thickness. The design has been studied with 3D finite element software. Simulations have given good results at 9 GHz with an insertion loss level of 1 dB and an isolation around 31 dB. A prototype has been manufactured based on the proposed design. An isolation of 36 dB has been measured but the insertion loss reached 5 dB. A small shift in the central frequency has been also observed since it was difficult to control the applied bias field. Nevertheless, this device and its characteristics are very interesting, considering the small amount of ferrite material used in the device, and considering that the structure is fully compatible with low cost industrial processes. These results allow us to draw some perspectives. One key point in the study will be the control of the magnetic bias field and the study of the sensibility of the adaptation according to geometrical and external conditions.

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