Analysis and optimization of a coplanar isolator for microwave systems

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***Abstract*—The miniaturization of circuits and the increasing frequency are two important issues of future communication systems and non-destructive testing equipment. This requires a high degree of integration and higher performance at reduced cost. The objective of this work is the study of a coplanar isolator for telecom applications. This isolator is constructed with a coplanar line charged by a ferrimagnetic material. We have started with an analytical study of a coplanar isolator, this allowed us to highlight the essential parameters influencing on the performances of our isolator, which are the longitudinal component of the magnetic field and the imaginary part of the non diagonal terms of permeability tensor. This confirms the importance of ferrite in the operation of our component. Then, we have contributed to the development of a resonance coplanar isolator using the simulator HFSS (High Frequency Structure Simulator) which concurrential comparatively to other works advantageous. The simulation results are very encouraging because we get insertion losses less than 2 dB and isolation more than 28 dB.**

Keywords-Magnetic material; microwave; non reciprocal passive component; Coplanar isolator; Ferrite.)

I. INTRODUCTION

Currently, the integration of non reciprocal microwave components, such as isolators or circulators, provides a major focus for research. These components are based on the gyromagnetic resonance of the ferrite [1]. The ferrite bulk substrate is magnetized by a constant magnetic field, which makes this kind of device noncompatible with monolithic microwave integrated circuit (MMIC) technology and only available in discrete packages.

On the other hand, the active components that are completely integrated show a higher noise level, insertion losses and a lower frequency range than the passive devices. Consequently, the development of devices integrating a ferrite and a semiconductor chip is a major focus of current research. A coplanar ferrite isolator is adopted because it is built with coplanar strips on a dielectric substrate and needs only a small quantity of ferrite material in the slots [2].

In this work, we will propose an analytical study to evaluate the propagation constant of a coplanar waveguide (CPW) with magnetic inclusions in the slots. Finally, we will contribute to the development of a resonance coplanar isolator using the simulator HFSS (High Frequency Structure Simulator).

II. THEORETICAL STUDY

A. Coplanar structure

A coplanar line consists of a strip of thin metallic film on the surface of a dielectric slab with two ground electrodes running adjacent and parallel to the strip. This line offers the advantage of allowing the connection surface (without using) discrete components. The obtained non-reciprocal effects on a coplanar line having a dielectric substrate on which two ferrite rods are placed at the substrate-air interface has been demonstrated [3]. The structure used here is shown in Figure 1.

The presence of the longitudinal component of the magnetic field is necessary to obtain non-reciprocal effects in the configuration we used. It is characteristic of propagation in a non-TEM (Transverse Electric-Magnetic) mode. Since, because the fundamental mode of a coplanar line is quasi-TEM, this component has generally low value [4].

To have important non-reciprocal effects, it is necessary to render maximum this component. The works done by B. Bayad [4] and by T. Rouiller and al. [5] show that the magnitude of the longitudinal component can be improved by the use of a high permittivity substrate, in addition the operation will be best at high frequency.

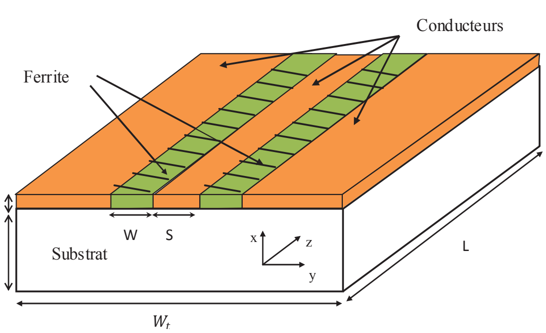

Figure 1. Coplanar isolator.

B. Origin of the phenomenon

The magnetic bias (H_{DC}) is applied along the axis (Oy) (Figure 2). The internal field H_i in the material depends on both of the demagnetization factor N and the external field H_e [6], [7]:

$$H_i = H_e - N \quad (1)$$

$$M = \overline{\overline{\chi}} H_i \quad (2)$$

With:

$$\overline{\overline{\chi}} = \begin{bmatrix} \chi & 0 & -jk \\ 0 & \mu & 0 \\ +jk & 0 & \chi \end{bmatrix} \quad (3)$$

$$jk = \frac{j\omega\omega_m}{(\omega_0 + j\alpha\omega)^2 - \omega^2} \quad (4)$$

$$\chi = \frac{(\omega_0 + j\alpha\omega)\omega_m}{(\omega_0 + j\alpha\omega)^2 - \omega^2} \quad (5)$$

$$\omega_m = \gamma M_s \quad (6)$$

Where ω is the angular frequency, ω_0 is the gyromagnetic resonance frequency, α is a damping factor, γ is the gyromagnetic ratio and M_s is the saturation magnetization.

Then can get:

$$H_{ix} = H_{ex} - N_x M_x = H_{ex} - N_x (\chi H_{ix} - jkH_{iz}) \quad (7.a)$$

$$H_{iz} = H_{ez} - N_z M_z = H_{ez} - N_z (\chi H_{iz} - jkH_{ix}) \quad (7.b)$$

If the rod is infinitely long, then $N_z \longrightarrow 0$:

$$H_{iz} = H_{ez} \quad (8.a)$$

$$H_{iz} = H_{ez} \frac{1 + jkN_x}{1 - \chi N_x} \quad (8.b)$$

Equation (8.a) shows that the internal longitudinal field is identical to the external longitudinal field because it is not diminished by the presence of demagnetizing field.

The results of the approach in the frequency domain shows that the polarization of the magnetic field is elliptical, we can define an ellipticity report such as:

$$\frac{H_{ez}}{H_{ex}} = j\ e_a \quad (9.a)$$

$$\frac{H_{iz}}{H_{ix}} = j\ e_b = j\ e_a \frac{1 + jkN_x}{1 - \chi N_x e_x} \quad (9.b)$$

The real parts of e_a and e_b reflect respectively the ellipticity of the polarization of the external magnetic field H_e and the internal field H_i in the plane (*Oxz*).

When the direction of application of the continuous magnetic field is reversed, the sign of the term k of the permeability tensor changes. The polarization of the magnetization becomes:

$$\left(\frac{M_z}{M_x}\right)^{\pm} = j \frac{\pm\left(\frac{k}{\chi}\right) + e_b}{1 \pm \left(\frac{k}{\chi}\right) e_b} \quad (10)$$

If $\omega \longrightarrow \omega_r$, we find [2]:

$$\left(\frac{M_z}{M_x}\right)^{\pm} = \pm j \quad (11)$$

When the direction of rotation of H_i coincides with that of magnetization vector (*M*), there is a high interaction therefore the electromagnetic wave is absorbed. In the contrary case, the interaction is low and there is little absorption (Figure 2). This phenomenon is the origin of the non-reciprocal effects.

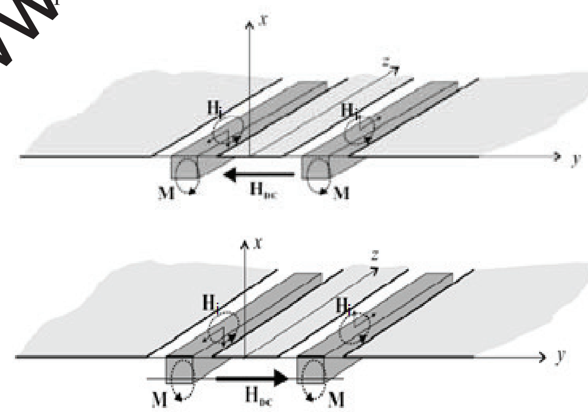

Figure 2. Interaction between the elliptical polarization of the internal field and the magnetic moment by the application of continuous magnetic field.

C. Coefficients of propagation

After having demonstrated the presence of non-reciprocal effect, we will now try to determine the coefficients of propagation.

From Maxwell's equations:

$$\nabla \vec{E} = -\frac{d\vec{B}}{dt} \quad (12)$$

We have then for the line with and without inclusions:

$$\frac{dE_{iz}}{dy} - \frac{dE_{iy}}{dz} = \frac{dB_{ix}}{dt} \quad (13.a)$$

$$\frac{dE_{ez}}{dy} - \frac{dE_{ey}}{dz} = \frac{dB_{ex}}{dt} \quad (13.b)$$

The corresponding magnetic inductions are:

$$B_{ix} = \mu_0 (\chi + 1) H_{ix} - jkH_{iy} \quad (14.a)$$

$$B_{ex} = \mu_0 H_{ex} \quad (14.b)$$

If the permittivity of the ferrite is close to that of the dielectric substrate, we can consider that the tangential electric field components and their derivatives are continuous [2], [6]:

$$E_{iz} \approx E_{ey} \quad (15.a)$$

$$\frac{dE_{iz}}{dy} = \frac{dE_{ez}}{dy} \quad (15.b)$$

$$\frac{dE_{ey}}{dz} = -j\beta_0 E_{ey} \quad (15.c)$$

$$\frac{dE_{iy}}{dz} = -j\beta_i E_{iy} \quad (15.d)$$

In case of an elongated rod ($N_z = 0$), we finally obtain for the two directions of continuous field (change of sign of k):

$$\beta_i^{\pm} = \beta_0 - \omega\mu_0 \frac{1 - N_x H_{ex}}{1 + \chi N_x H_{ey}} \left(\chi \pm k \frac{H_{ez}}{jH_{ex}} \right) \quad (16)$$

This relation shows the influence of the anisotropic properties of the ferrite and the ellipticity (H_{ez}/jH_{ex}) of the microwave magnetic field on the nonreciprocity of the device ($\beta_i^+ - \beta_i^-$).

The longitudinal component H_{ez} can be improved by using a substrate with high relative permittivity and sufficiently thick [2]. The operation will be also better at high frequency and with large slots.

III. RESULTS AND DISCUSSIONS

The results are obtained from Ansoft HFSS software, which is based on a three dimensional electromagnetic finite elements simulator.

The simulated structure is represented in Figure 1. In all simulation, ours isolators are formed from the following materials: gold conductors, ferrite YIG (Yttrium Iron Garnet) and alumina substrate, since the wave interacts with the substrate, we have simulated coplanar isolators fabricated from different dielectric permittivities substrates.

A. *The initial structure*

The initial structure has the dimensions given in Table I.

TABLE I. DIMENSIONS OF THE INITIAL STRUCTURE

L	W_t	S	W	h	d	t
10mm	4mm	0.4mm	0.4mm	0.635mm	0.1mm	0.1mm

The Figure 3 shows the obtained transmission parameters for initial structure. We can see a phenomenon of non-reciprocity effect (peak) around 10.5 GHz (Non-Reciprocity Effect: NRE = 4.57). Thus, the insertion losses (IL) are high and the isolation (IS) is low (5.97 dB and 10.54 dB respectively).

In the following study, we will try to improve these values to achieve the best features (low insertion losses and high isolation).

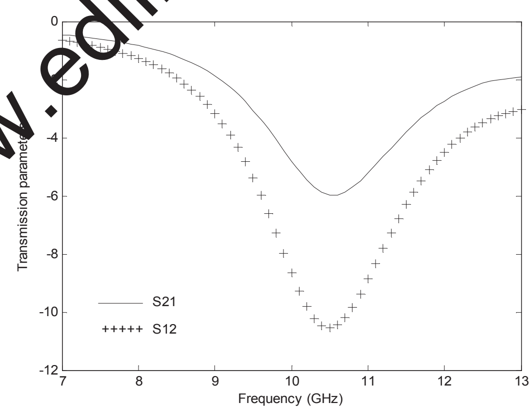

Figure 3. Transmiission parameters for initial structure.

B. *Effect of dimensional parameters*

The table II gives the variations of the transmission parameters according to the thickness of ferrite, we note that the other dimensions parameters are fixed. We see that as the layers are thicker as the isolation increases, when the thickness increases, the insertion losses also increase, this result does not satisfy the requirements of our component.

TABLE II. VARIATIONS IN PERFORMANCE OF THE ISOLATOR COPLANAR DEPENDING ON THE THICKNESS OF THE FERRITE LAYER.

Ferrite thickness [mm]	$f_r[GHz]$	$IL(dB)$	$IS(dB)$	$NRE(dB)$
0.05	10.6	2.84	5.31	2.47
0.10	10.5	5.97	10.54	4.57
0.15	10.4	10.29	15.73	5.44
0.25	10.1	14.63	20.83	6.20

The table III gives the variations of transmission parameters according to the thickness of conductors, we note that the other dimensions parameters are fixed. We can see that the increase in the thickness of the conductors involves a reduction of insertion losses unfortunately, isolation and NRE also decrease.

TABLE III. VARIATIONS IN PERFORMANCE OF THE ISOLATOR COPLANAR DEPENDING ON THE THICKNESS OF THE CONDUCTORS LAYERS.

conductors thickness [mm]	$f_r[GHz]$	$IL(dB)$	$IS(dB)$	$NRE(dB)$
0.05	10.3	6.63	12.98	6.35
0.10	10.3	5.80	12.32	6.52
0.20	10.3	4.77	10.83	6.06
0.30	10.3	3.63	9.62	5.99

C. *Effect of the nature of the substrat*

The table IV gives the variations of transmission parameters according to nature of the substrate. We can see that if a substrate with a high relative permittivity is used, the insertion losses decreases and isolation increases. This result correlates well with the previous works. Thus, we note that the use of high relative permittivity substrate does not change the functional zone of the isolator (maximum of NRE in table IV located substantially around 10.3 GHz). We can justify this result by the fact that the use of a high-permittivity substrate causes an increase in ellipticity ratio of the microwave signal in the ferrite-dielectric interface, which increases isolation and minimizes insertion losses.

TABLE IV. VARIATIONS IN PERFORMANCES OF THE COPLANAR ISOLATOR ACCORDING TO NATURE OF THE SUBSTRATE.

relative permittivity (ε_r^s)	$f_r[GHz]$	$IL(dB)$	$IS(dB)$	$NRE(dB)$
9.4	10.4	5.23	11.98	6.75
20	10.4	4.01	18.05	14.04
30	10.3	3.30	24.87	21.57
40	10.3	2.87	32.33	29.46
50	10.3	2.49	40.13	37.64

By associating the effects indicated above, we can establish a global model of the structure (Figure 4) which takes advantage of each of the positive influences. It is firstly characterized by a substrate with a relative permittivity of 40 and the YIG ferrite which is compatible with our operation in band X. The final model of the structure has the dimensions shown in the table V.

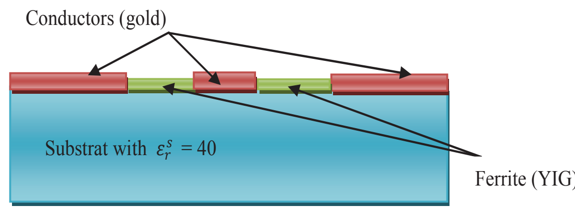

Figure 4. Model of the final structure.

TABLE V. DIMENSIONS OF THE FINAL STRUCTURE

L	W_t	S	W	h	d	t
10mm	4mm	0.4mm	0.6mm	0.635mm	0.14mm	0.1mm

The figure 5 shows the performances of the final structure. In comparison to the initial structure, we have reached a significant improvement of all parameters for a good coplanar isolator operating around of 10 GHz, which isolation is increased from 10.54 dB to 28.86 dB and the insertion losses are decreased from 5.97 dB to 1.94 dB.

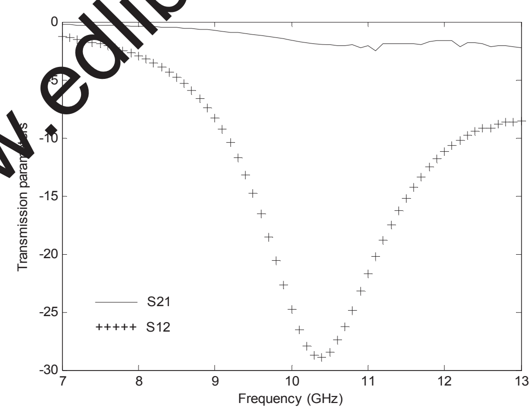

Figure 5. Transmission parameters for final structure.

IV. CONCLUSION

A simple and explicit analytical study for evaluate the propagation constant method for evaluating the propagation constants of a nonreciprocal coplanar isolator has been presented, this allowed us to highlight the essential parameters that influencing on the performances of our isolator, which are: the longitudinal component of the magnetic field H_z and the imaginary part of the non diagonal terms k of permeability tensor. This confirms the importance of ferrite in the functioning of this component.

A coplanar isolator has been optimized and simulated. This device has only required a ferrite YIG film of 0.14 mm thickness. The device has been studied with 3D finite element software.

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