# Design of a Coplanar Circulator Based on Thick and Thin Ferrite Film

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**Abstract:** *This paper takes place in the field of passive microwave components. Coming from the requirements of mobile communication devices, miniaturization of microwave components is needed. Aimed at this objective, for several years we have been working on the development of a miniature planar circulator. The main aim of this paper is to show the circulator with different ferrite thickness and then to present a method to reduce the insertion loss of the circulator in function of the thickness of the ferrite film. The circulator is designed with new topology coplanar/microstrip. The analytical structure based on stripline circulator and analysed by using a three dimensional finite-element method. The circulator is then fabricated, and its properties in the microwave range are characterised using a network analyser and a probing system. An additional part for the isolator with non-symmetrical was designed in order to reduce the insertion loss in the conductor and to obtain a large bandwidth compared to the existing devices.*

**Keywords***:* *Coplanar circulator/isolator, non-reciprocal passive component, ferrite film, miniaturization, insertion loss.*

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## 1. Introduction

Thispaper deals with passive microwave components like circulator or isolator, caused by growing needs in telecommunications, studies in microwave electronic materials were strongly increased. In this field of research, we are able to make two types of ferrite films: the thick and the thin films. Working on these magnetic materials are always making progress in order to develop new industrial processes compatible with the miniaturization of microwave components.

The important points to these components lie in using Yttrium Iron Garnet (YIG) thick and thin films, and in the fact that the accesses to the device are Coplanar Wave guide (CPW). These devices usually exploit two main physical effects characterising soft ferrites are the gyro-resonance and the field displacement.

In this paper we will present three main aspects of our coplanar circulator, in order to obtain the final CPW circulator with a few insertion losses recommended by the industry. These three aspects are Analytical, numerical and experimental.

The circulators are designed according to some approximate rules which are well-known but are specific to stripline circulators. As a result, for a coplanar circulator, an optimization of the initial design must be performed before obtaining a functional device. The design and S-parameters are based on the theoretical results obtained from a stripline structure [2, 3]. These outcomes are then transposed to a coplanar design after a numerical study.

Many scientists studied the transmission characteristics of Y-junctions stripline circulators since Bosma's work in the sixties [2, 3], but there are few papers talking about coplanar circulators. Here are some of the most significant designs that we have found in the literature. Ogasawara and Kaji [7], Koshiji and Shu [5] and Oshiro *et al*. [8]. All of them employed a bulk piece of ferrite.

Our objective is to prove that it is possible to make a miniature circulator with 1000, 100 and 65 µm ferrite films. As the manufacturing process developed in our laboratory allows making YIG thin films with 16 µm, then it will be possible for us to prospect for collective fabrication in order to reduce the production costs.

Several sets of simulations are done using Ansoft High Frequency Structure Simulator (HFSS), which includeshigh frequency electromagnetic simulations based on the three dimensional Finite Elements Method (FEM). In simulations, the ferrite is modelled using Polder's tensor [9], these simulationsare carried out to estimate the behavior of the component. In our study many parameters of the CPW are analyzed in order to quantify their effects on circulators performance. Specific physical parameters that have been used.

The YIG film have been modelled with a dielectric constant $\varepsilon_r$ = 15.3, a dielectric loss tangent with a maximum of tan $\delta$=2.10$^{-4}$ (typical values at 8.3 GHz, given by the Temex company for massive ferrite film), a saturation magnetization $\mu_0 M_s$= 175 mT and a Ferromagnetic Resonance (FMR) line width $\Delta H$=3.5 kA/m Oe. For conductor lines made of gold, the conductivity is $\sigma$ = 41.10$^6$ S/m. The ferrite is supposed to be saturated and the internal bias field is supposed to be uniform.

Many fabricated circulators have thicknesses that vary between 1000 and 16 µm. These structures present the advantage of new topology coplanar/microstrip, where a non-connected ground is placed between the alumina substrate and the ferrite film. Both Line and Ground are located in the same plane; hence it can be easily fabricated at low cost by using a lithography process. This method permits us to reduce the number of manufacturing steps as well as facilitates the interconnection with other microwave circuits.

All of these structures were measured using three GSG coplanar probes which are connected with a vector network analyzer. The main aim in this paper is to reduce the value of the insertion loss for the presented structure by reducing the access length.

## 2. Analytical and Numerical Studies

### 2.1. Analytical Study of a Stripline Circulator

The stripline circulator is studied with the usual analytical method. The aim is to design a circulator with a YIG film. So, when the stripline circulator functions properly with the magnetic film, the effect of several parameters on the performance is evaluated using a numerical model. After an optimized design is obtained, we transform the circulator into its coplanar version and we finish the study with numerical adjustments.

The stripline circulator is composed of a circular inner conductor from which three 120° oriented striplines start. Above and below of this inner conductor, there are two circular discs of YIG, then two ground planes are closing the structure (see Figure 1).

From the theoretical results obtained by Bosma [2, 3], design rules were achieved, resulting in possible dimensions for a functional Y-junction stripline circulator. The formulas are based on the use of Green's functions. Simulations were performed using an soft HFSS to make sure that the theoretical dimensions are suitable for a real design.

For the first resonance mode of the disk of ferrite, we have used the first root of the derivative of the first order Bessel function($x=x_{1,1}=1.84$). With the material parameters specified in the introduction, we have derived the conductor radius of $R$=2 mm.

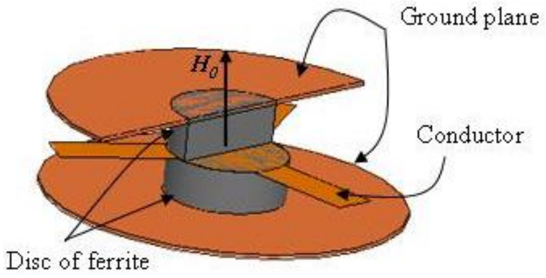


Figure 1. Y-junction Stripline circulator.

### 2.2. Numerical Study of Stripline Circulator

With the material parameters given in the introduction, we have made a set of simulationsvarying the geometrical parameters, to make sure that our optimization and modelling were good enough [11]. We have the ferrite thickness to 20 µm.

#### 2.2.1. Conductor Radius R

Bosma [3] assumed that the radius of the ferrite is the same as one of the conductor lines ($r = R$).The Radius $R$ of ferrite disks is extracted from of the conductor has been changed from [3].

$$x = kR = w\sqrt{\varepsilon\varepsilon_0\mu_{eff}\mu_0} \qquad \text{where } \mu_{eff} = \frac{\mu^2-\kappa^2}{\mu} \tag{1}$$

And

- $\varepsilon_0$ is the free space permittivity,
- $\mu_0$ is the free space permeability,
- $\varepsilon$ is the relative permittivity of the ferrite,
- $\mu_{eff}$ is the effective permeability of the ferrite derived from the elements of the magnetic Polder's tensor [9]. For the first resonance mode of the disk of ferrite, we have used the first root of the derivative of the first order Bessel function ($x=x_{1,1}=1.84$).

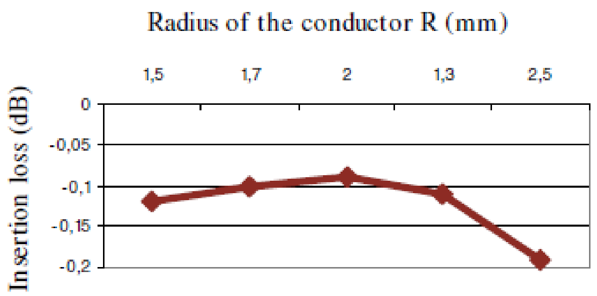


Figure 2. Numerical results for the insertion loss of the stripline circulator as a function of the radius of the conductor.

With the material parameters given in the introduction, we have derived the value $R$=2 mm.

Using this value, we have made a set of simulations to be sure of our optimization and modelling. The radius of the conductor has been changed from 1.5 to

2.5 mm, as shown in Figure 2. The insertion loss has reached the minimum value at *R* equal to 2 mm.

#### 2.2.2. Conductor width W

The stripline conductor width has been derived from equation (2) as a function of the radius R of the ferrite disks and the stripline width angle Ψ (3) [2].

$$W = 2\,R\,sin\varphi \quad (2)$$

$$\text{Where } \Psi = \frac{1}{\sqrt{3}} \times \frac{\pi(\kappa/\mu)}{1.84\sqrt{\mu_{eff}/\varepsilon}} \quad (3)$$

The effect of this geometric parameter on circulator performances has been studied in order to optimize the non- reciprocal component. Simulations with various values of the stripline width W have been performed (see Figure 3) [11]. The insertion loss has reached the minimum value at W = 400µm. After W=500µm the insertion losses decreased rapidly

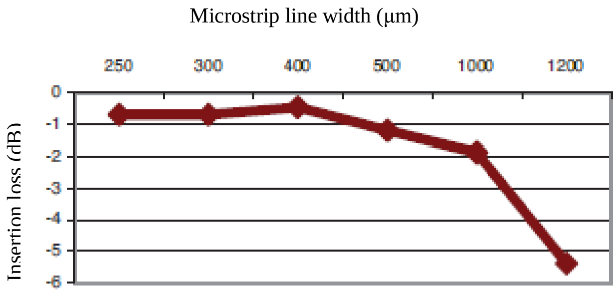


Figure 3. Numerical results for the insertion loss of a striplinecirculator as a function of signal line width W.

#### 2.2.3. Effect of the Magnetic Bias Field Hi

The component is polarized and the internal magnetic field $H_i$ in the YIG film is given by:

$$Hi = H_{dc} + H_a - N_z M_s \quad (4)$$

Where

- $H_{dc}$ is the external magnetic field ($H_{dc}$ = 636 kA/m),
- $H_a$ is the anisotropy field ($H_a$ = 0 for the YIG),
- $N_z$ is the demagnetizing factor ($Nz$ = 1 for a thin film),
- *Ms* is the saturation magnetization of the material. The obtained value of the internal magnetic field ($H_i$) is 557 kA/m which is uniformly applied to the YIG ferrite thin film.

In order to estimate the sensibility of losses up to the external bias field, we have made several simulations with different values of $H_i$.

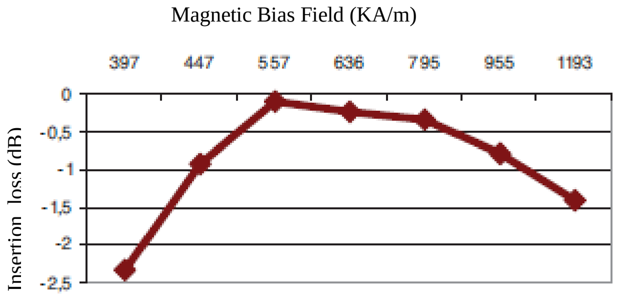


Figure 3. Numerical results for the insertion loss of our striplinecirculator as a function of magnetic bias field *Hi*.

Results are reported on Figure 3. The best value between 397 kA/m and 1193 kA/m is 557 kA/m. For this polarization, insertion losses are better than −0.5 dB.

### 2.3. Comparison between Analytical and Numerical Results

To evaluate the performance of the circulator, we calculated the S parameters of the dispersion matrix. In our case, the general expression of the dispersion matrix is:

$$S = \begin{bmatrix} S_{11} & S_{31} & S_{21} \\ S_{21} & S_{11} & S_{31} \\ S_{31} & S_{21} & S_{11} \end{bmatrix} \quad (5)$$

It is now supposed that the coefficients of return loss ($S11$), isolation ($S31$) and insertion loss ($S21$) referenced to port 1 are identical for port 2 and 3.

The *S*-parameters calculations are based on Neider's study [6] considering the losses in the conductor of the stripline circulator. The results from the analytical model are compared with the HFSS numerical results (see Figure 4).

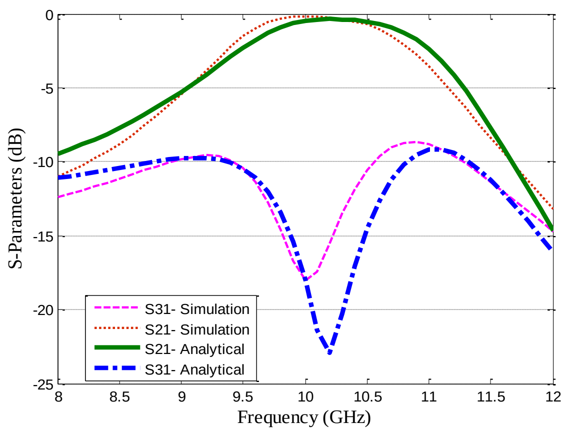


Figure 4. Evolution of S-parameters for the analytical and numerical studies [11].

The levels of isolation and insertion loss obtained by simulation are equivalent to those obtained from the analytical model. However, we can observe a little shift in frequency between the analytical and the numerical method.

As a conclusion for this part, these studies serve as a basis for the design of the new CPW circulator in order to facilitate the transposed the stripline design to the coplanar one.

## 3. Design of the Coplanar Circulator

The analytical and numerical modelling must now be transposed onto a coplanar circulator design. The proposed structure of our circulator is shown in Figure 5. The circulator has a hexagonal shape and three ports (the impedance of each one is referenced to 50 Ω) connected in a 120° Y-junction. The analytical values obtained from part II for the stripline have been used to obtain the final design of the CPW structure. The radius of the inner conductor is R = 2mm and the width of the access lines is W = 400 µm (Figure 5).

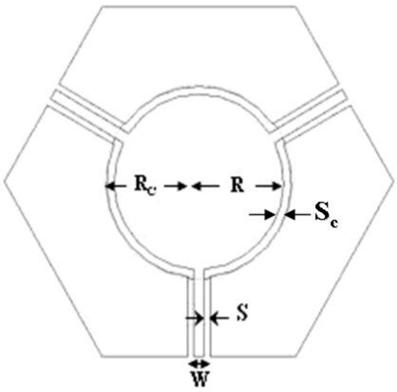


Figure 5. Top view with geometrical parameters.

### 3.1. Coplanar Circulator with Thin Film

Figure 6shows 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 6 the signal line and the ground plane of the CPW are located in an identical plane over the YIG film of thickness 20, 65 and 100 µm ($h_f$) respectively. This magnetic film is placed over a 635 µm ($h_{al}$) of commercial alumina substrate (with the permittivity εr = 9.2 and the dielectric loss tangent tanδ = 6.10-4 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 center of the circulator [11]. Finally, a magnetic bias field ($H_{dc}$ = 477 kA/m) is applied, perpendicular, to the YIG layer.

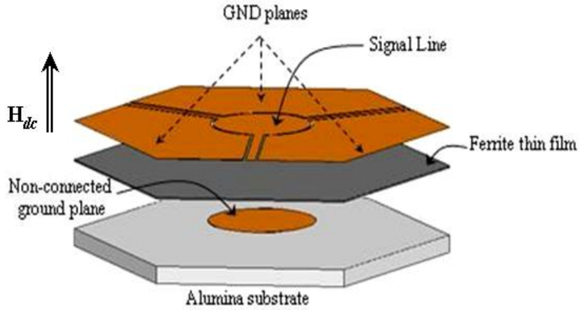


Figure 6. Structure of the thin film coplanar circulator: showing the different stages.

### 3.2. Coplanar Circulator with Thick Film

Figure 7 shows also 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 7 the signal line and the ground plane of the CPW are located in an identical plane over the YIG film of thickness 500 and 1000 µm ($h_f$) respectively. The lower non-connected ground plane is positioned under the ferrite substrate. Finally, a magnetic bias field ($H_{dc}$= 258 kA/m) is applied, perpendicular, to the YIG layer.

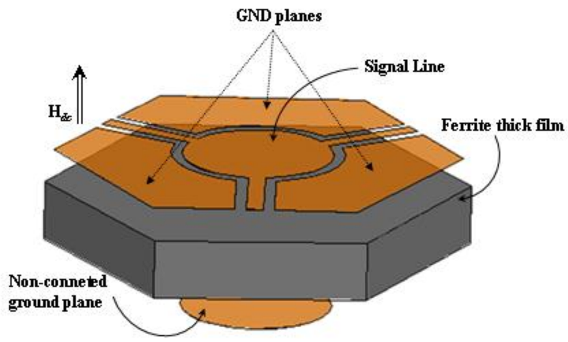


Figure 7. Structure of the thick film coplanar circulator: showing the different stages.

## 4. Simulation Results

A series of simulations using Ansoft HFSS are carried out in order to estimate the behavior of the component. Three main parameters of the CPW were tuned in order to quantify their effect on the component's circulator performances.

### 4.1. Effect of the S, Sc and Rc

The effect of Line-to-GND (ground) spacing 'S' on transmission characteristic has been studied [11]. We state that the best transmission properties are obtained for S = 130 µm. Also the Disk-to-GNG spacing (Sc).

As long as the radius of the lower non-connected ground plane (Rc) have been studied in [11]**Error! Reference source not found.**and it was concluded that their optimized values were 150 µm and 2.13 mm respectively. All these results were made assuming identical ferrite thickness of 20 µm.

## 4.2. Simulation Results For 20 µm Thick Ferrite

The simulated model of the circulator with ferrite thickness of 20 µm is shown on Figure 6. The geometry of the design is optimized using the HFSS software. The design frequency is 10 GHz. The simulated S-parameters of the circulator are shown in Figure 8. Non-reciprocal transmission behavior was found at 10 GHz. The insertion loss |S21| is 1.5 dB, the isolation |S12| is 22 dB and the return loss |S11| is 31 dB.

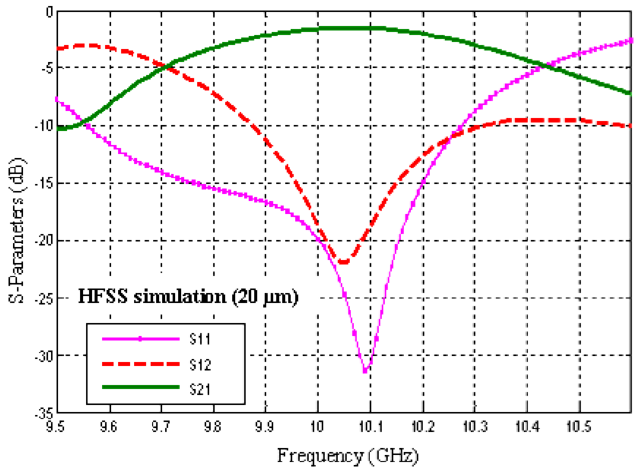


Figure 8. Simulation (Insertion loss, isolation and return loss) results of coplanar circulator with 20µm ferrite film.

## 4.3. Simulation Results for 65 µm Thick Ferrite

The simulated model for the 65 µm thick circulator is the same as previous (Figure 6). The geometry of the design is optimized using the HFSS software. The design frequency is 9 GHz.
The simulation model of the circulator is shown in Figure 8.The geometry of the design is optimized using the HFSS software. The design frequency is 9 GHz. The dimensions (see Figure 6) 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).
- $R_c$=2.23mm (Radius of the non-connected ground plane).
- $h_{ferrite}$=65µm.
- $h_{lumina}$=635 µm.

The simulated S-parameters of the circulator are shown in Figure 9 [12]. Best non-reciprocal transmission behavior 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.

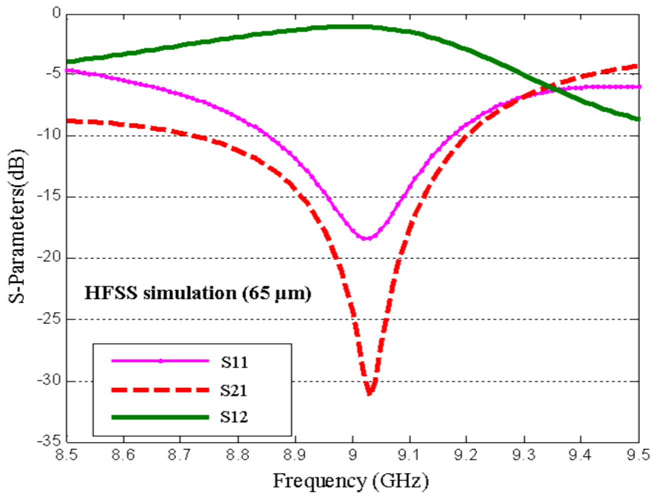


Figure 9. Simulation (Insertion loss, isolation and return loss) results of coplanar circulator with 65µm ferrite film.

## 4.4. Simulation Result of 1000 µm

Figure 7shows the frequency dispersion of S-parameters for a circulator with a 1000µm YIG film. Non-reciprocal transmission characteristics are obtained at 12 GHz (see Figure 10) with -0.63 dB for insertion loss, isolation of -20.29 dB and - 25.36 dB for the return loss S11.

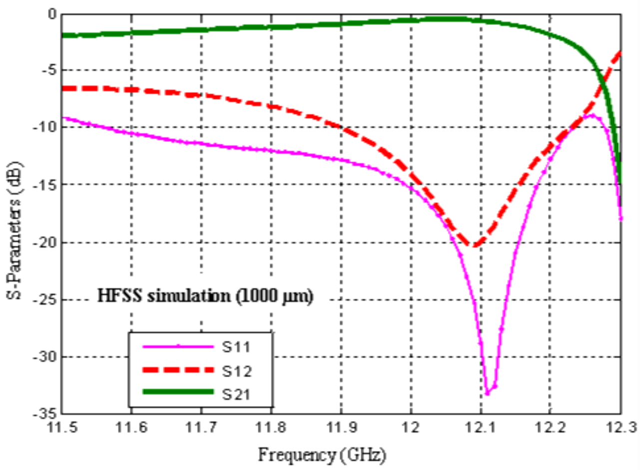


Figure 10. Simulation (Insertion loss, isolation and return loss) results of coplanar circulator with 1000µm ferrite film.

## 4.5. Parametric Study: Ferrite's Thickness

Figure 11 shows the performance of the circulators a function of the thickness of the ferrite film [11]. The losses increase when the thickness of the ferrite decreases. For each set of parameters, an optimization process is realized, but we cannot argue that obtained results are the best ones for each structure. Therefore, we must be careful in analyzing the results of Figure 11.

Nevertheless, the only characteristic which gives a regular variation is the "insertion loss", thus we can conclude that the reduction of the ferrite thickness (from 100 µm to 10 µm) increases the losses dramatically [1, 4].

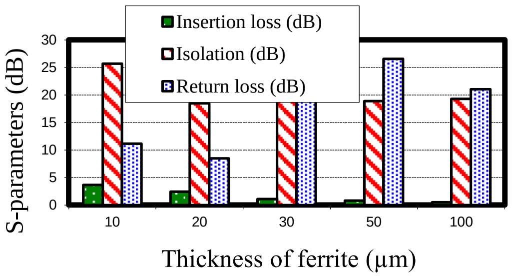


Figure 11. *S*-Parameters (*S*21, *S*12, *S*11) of a coplanar circulator as a function of the thickness of the ferrite.

As a conclusion of this part; It is possible to make CPW circulator of a stripline Y-junction circulator. The advantage of the CPW configuration is that it facilitates its fabrication and also that such a component it easy to measure with our bench (see parts V and VI). The simulated model shows very good behavior at about 10 GHz.

## 5. Fabrication and Measurements of the Circulator

Following the analytical and numerical studies for the stripline and coplanar circulator, a set of prototypes were fabricated using various ferrite thicknesses. The transmission characteristic of the circulator was measured using a Vector Network Analyzer (VNA) associated to a CPW probe station. The measurement bench is equipped with 3 probes oriented at 120° from each other. The probes have a coplanar GSG configuration.

As we use a 2-port VNA for the measurement, it is necessary to connect one of the three branches to a 50 $\Omega$ matched load (see Figure 12).

Furthermore, in order to polarize the ferrite, a magnetic bias field is realized using two permanent magnets placed above and below the device.

Figure 12. Three-probe system.

### 5.1. Circulator with 16 µm Ferrite Film [10]

The coplanar circulator with 16 µm YIG thin films has been deposited on alumina substrate by using RF sputtering magnetron. The physico-chemical and the magnetostatic properties have been studied. The XRD patterns of the films annealed at 740 °C during 2 hours shows a correct diffraction pattern, the thin films being polycrystalline and randomly oriented. The obtained YIG film, once polarized, has a magnetization of 150 mT which is close to the expected YIG value (178 mT). The quality of the film surface was characterized using the SEM technique (details are shown in [12]).

The measured S-parameters are presented in Figure 13. A non-reciprocal effect of 8 dB at 10 GHz is obtained, with an insertion loss of 18 dB. The measured value of the insertion loss is high which may be ascribed to various reasons. The main being due to the high reflection occurring at port 1 as revealed by the S parameter value of -10 dB (Figure 13). This loss can be reduced by several methods that will be given after.

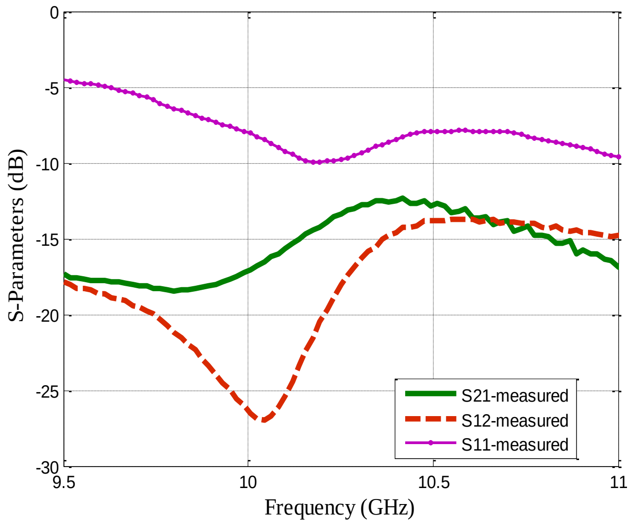


Figure 13. Experimental (Insertion loss, isolation and return loss) results of coplanar circulator with 16µm ferrite film.

### 5.2. Circulator with 65 µm Ferrite Film [9]

The 65 µm ferrite film is obtained by grinding a commercial ferrite slab (see Figure 14). 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. The copper Signal Line and GND planes have a thickness of 4 µm. They are patterned on the YIG ferrite using lift-off process.

Figure 14. Grinding machine used for the commercial ferrite slab to obtain the 65 µm.

The measured of S-Parameters are presented in Figure 15. As we see, significant non-reciprocal transmission behaviour is found at 9.1 GHz. The insertion loss |S12| is about 5 dB, the isolation |S21| is 36 dB, the return loss |S11| is 10 dB and the bandwidth (at 20 dB) is 115 MHz.

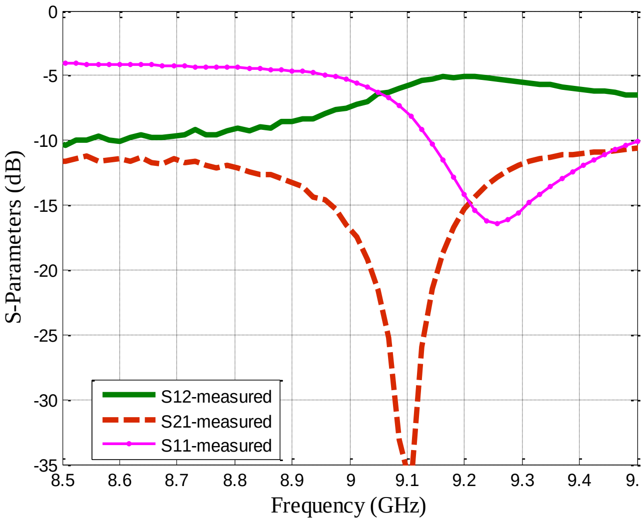


Figure 15. Experimental (Insertion loss, isolation and return loss) results of the coplanar circulator with 65 μm thick film.

### 5.3. Circulator with 1000 μm Ferrite Film

Also we have fabricated a circulator with ferrite thickness of 1000μm. This stepis very advised to realize by using a bulk ferrite. Figure 16 shows the frequency characteristics of the S-parameters. Non-reciprocal transmission characteristics were obtained at 12 GHz with the insertion loss |S21| of 4 dB, the isolation |S12| of 18 dB, the return loss |S11| of 30 dB.

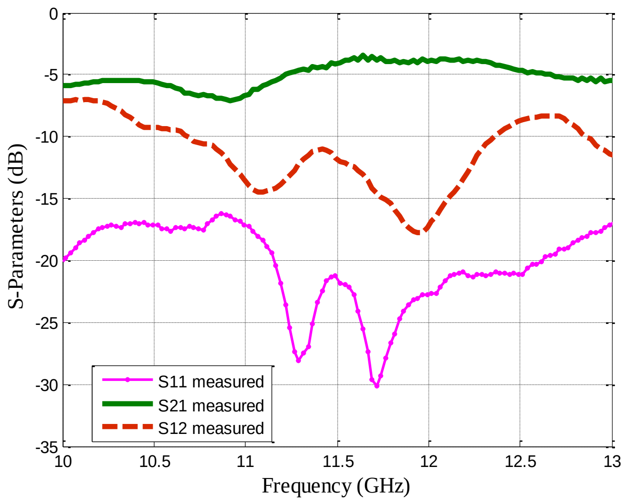


Figure 16. Experimental (Insertion loss, isolation and return loss) results of coplanar circulator with 1000μm ferritefilm.

Table shows the S parameters of circulators with different thicknesses. The value of insertion -4 dB for the initial prototype 1 and we obtain isolation of the order of -18 dB with a thickness of 1000 μm. For a thickness of 65 and 16 μm, the losses are - 5 and -12 dB respectively (see Table).

Table 1. Geometrical parameters and performances of threeprototypes with 1000, 65 and 16 μm ferrite thickness respectively.

| | Prototype 1 | Prototype 2 | Prototype 3 |
|---|---|---|---|
| **W (μm)** | 250 | 400 | 400 |
| **S (μm)** | 75 | 130 | 130 |
| **Rc (μm)** | 180 | 180 | 180 |
| **R (mm)** | 2 | 2 | 2 |
| **Ferrite h (μm)** | 1000 | 65 | 16 |
| **Frequency (GHz)** | 12 | 9.2 | 10 |
| **S21 (dB)** | -4 | -36 | -26 |
| **S12 (dB)** | -18 | -5 | -12 |
| **S11 (dB)** | -30 | -16 | -19 |

## 6. Reducingthe Insertion Loss

There are many causes of loss and several methods to reduce the insertion losses for the circulator. First, the high reflection occurring at the ports as revealed by the S parameter value. This loss can be reduced by introducing a 50 Ω adaptation impedance on the different ports. Second, the functional frequency of the circulator is close to the resonance frequency of the ferrite, this also goes in the direction of increasing the losses. Third, the roughness of ferrite layer gives, as a result, rough conductors, as well as the losses of the conductor who becomes increasingly important when the thickness of ferrite films becomes thinner than 100 μm [10, 11].

Also, the misalignment between the non-connected ground plane and the central conductor contributes to the losses.

Another way to reduce some of insertion losses is to reduce the length of the access lines which should be as short as possible. Our structure has finally dimensions of about 6 × 6 × 0.7mm3 (see Figure 17).

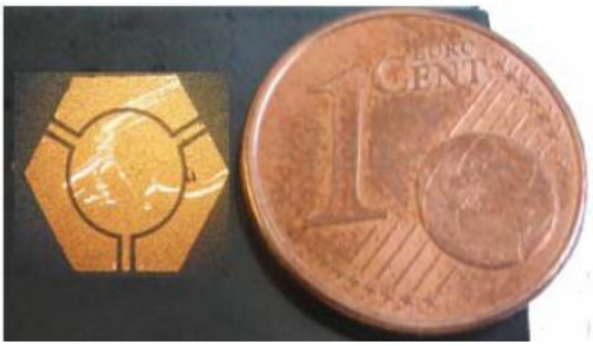


Figure 17. Photography of the circulator with shortened access lines.

Table shows the S parameters of circulators with different thicknesses. The value of insertion loss decreased to -3 dB (- 4 dB for the initial prototype) and we obtain isolation of the order of -21 dB (see Figure 18) with a thickness of 1000 μm. For a thickness of 65 μm, losses are also reduced from - 5 dB to -2 dB (see Figure 19).

Table 2. Geometrical parameters and performances of two prototypes with 1000 and 65 μm ferrite thickness after shortened the access lines.

| | Prototype 1 | Prototype 2 |
|---|---|---|
| **W (μm)** | 250 | 400 |
| **S (μm)** | 75 | 130 |
| **Rc (μm)** | 180 | 180 |
| **R (mm)** | 2 | 2 |
| **Ferrite h (μm)** | 1000 | 65 |
| **Frequency (GHz)** | 13.5 | 10.5 |
| **S21 (dB)** | -3 | -2 |
| **S12 (dB)** | -21 | -17.3 |
| **S11 (dB)** | -36 | -17.5 |

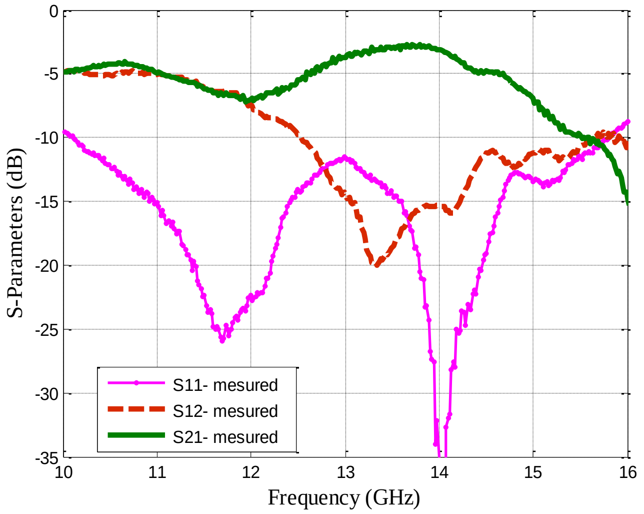


Figure 18. Experimental (Insertion loss, isolation and return loss) results of coplanar circulator with 1000μm ferrite film. (Prototype 1).

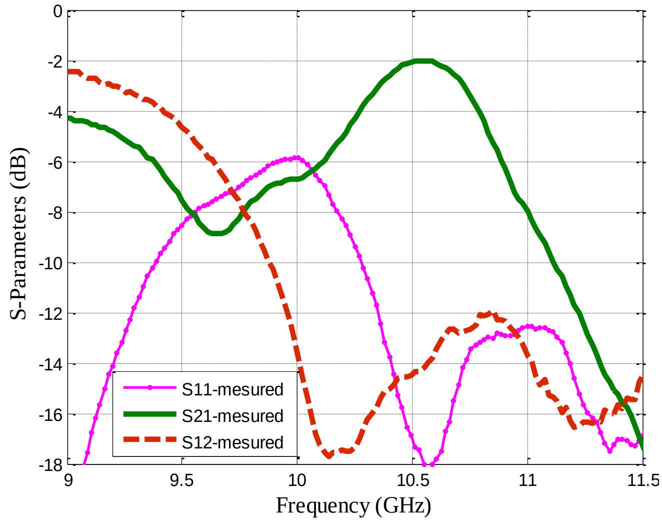


Figure 19. Experimental (Insertion loss, isolation and return loss) results of coplanar circulator with 65μm ferrite film. (Prototype 2).

## 6.1. Parametric Study: Ferrite's Thickness

The ferrite thickness is an essential parameter in the circulator with magnetic materials and it controls the quality of the signal which plays on the non-reciprocal effect obtained for the circulator. Figure 20 gives the comparison between the different S parameters, modeling under HFSS and their obtained by measured, of the circulator in function of the ferrite thickness. The losses increase when the thickness of the ferrite decreases. Thus we can conclude that the reduction of the ferrite thickness (from 1000 μm to 20 μm) increases the losses dramatically.

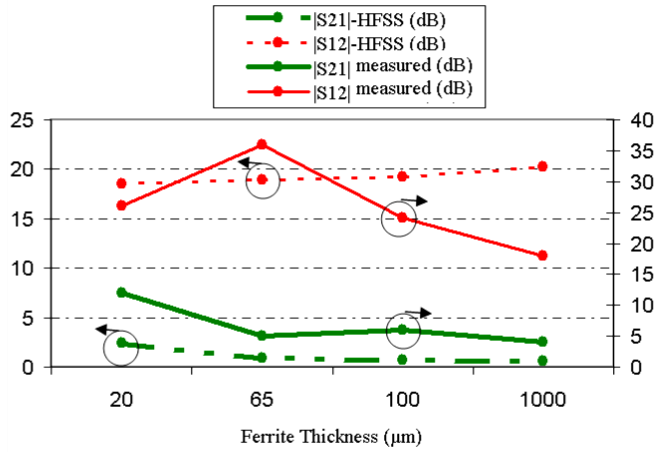


Figure 20. Comparison of S-Parameters ($S_{21}$, $S_{12}$) between HFSS and measure of a coplanar circulator as a function of the thickness of the ferrite.

As conclusion, the possibility of reducing the insertion losses by shortening the CPW access lines, because of the negative impact of the ferrite in the proximity of the access lines.

## 7. Conclusions

In this paper we proposed a new coplanar topology that takes advantage of two different structures, the microstrip at the device center, and the conventional structures of stripline at the connection level, to facilitate the connection of the component. This allows partial answer to the problem related to the integration of the circulators.

The electromagnetic analysis of coplanar circulator was developed based on the theory proposed by H. Bosma [3] which predicts the response of microwave circulator with microstrip technology. The influence of different geometric parameters on the performance of the circulator has been studied.

Since our main aim is to minimize the device through the use of thick ferrite film, the thickness parameter is studied in order to know their impact on the circulator performance. Following various simulations have been made to demonstrate the commercial feasibility of a technology solution integrating a non-connected metallic plan under the ferrite layer.

Finally, many prototypes were fabricated using various thicknesses ranging from1000 to65 μm. Then the transmission characteristics of these structures are measured using VNA associated to the probe station. The major results presented an acceptable non-reciprocal transmission characteristic as a practical circulator device.

Based on our experimental results, we were also able to decrease insertion losses by reducing the length of the access lines which should be as short as possible.

Further works will optimize the performance. Dimensions, applied field, material properties etc., must be defined to increase the isolation level, to reduce the insertion loss and to expand the band width. Moreover, this study has shown that the thinning of the ferrite film is possible without too much damaged performance. These promising prototypes could constitute new integrated circulator in telecommunication systems.

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