Rectangular Junction Ferrite Component in Millimeter Waves

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Abstract — The design of non reciprocal components still remains an important challenge for integrating new functions in microwave devices. Such passive components usually use magnetic materials like ferrites. For high frequency bands barium ferrite could be used without external magnets when the magnetic moments (a cristal axis) are directed moments. Barium ferrite thin films or composite material should be suitable materials for integrating non reciprocal microwave passive components. In this way a stripline structure as a rectangular ferrite junction is proposed. Two ferrite slabs are located between an inner conductor and two ground plane. Non reciprocal effects are observed and this rectangular junction ferrite component could be used as a circulator. 3D simulations results confirm this first approach.

1. INTRODUCTION

Non reciprocal microwave components in millimeter waves, such as circulators, are based on the gyro-resonance properties of a ferrite material. The integrating of self-biased ferrite devices seems to be possible using thin-film processes [1, 2] or composite materials which can be made from magnetic nano-particles scattered into a host dielectric matrix. To reach upper frequency bands, magnetic materials like barium ferrite, having a high magnetocrystalline anisotropy, can be used for self-biased devices when the magnetic moments (crystal axis) are directed without D.C. field being applied. For lower frequency applications, other ferrites or garnets like YIG, can be used with external magnets which unfortunately does not permit electronic integration.

So, to make high frequency ferrite devices suitable for integration, the use of thin-films with directed magnetic moments seems to be a good approach. The small thickness of these films emphasizes the theoretical approximations made by H. Bosma [3] in order to derive Green’s function of a Y-junction circulator.

The circular stripline structure of circulators requires bent access lines for connecting, which could disturb the TEM propagation and cause losses in higher frequency bands. Other circulator shapes and structures have been investigated. Microstrip and coplanar structures with several shapes (triangular, hexagonal.), were proposed [4, 5]. However, for structures different from the stripline structure, Green’s function method is not easy to be used. The boundary conditions must be correctly defined to obtain an analytical solution for rapid computing of scattering parameters (S parameters). So, in general, a 3D electromagnetic software is used but the simulation requires more computing time.

In this paper a simple structure, is studied as a “rectangular circulator” made from a stripline structure which allows us to derive Green’s function and to use it for the S parameter computing. However, a 3D software (HFSS) is also used because the analytical model still remains too simple to take into account non perfect boundary conditions.

2. THEORITICAL STUDY

The structure of the studied component is shown on Figure 1. The non-reciprocal effect is due to the field displacement when a D.C. magnetic field is applied (which corresponds to an internal field) to the ferrite slabs along the z-axis direction. An analytical model can be developed with the same approximations as the ones used by Bosma [3] for circular Y-junction circulator. Only the z-axis electric field component, the y-axis and x-axis magnetic field components are considered. A magnetic wall is referred to the ferrite edge. Green’s function method is used with inhomogeneous boundary conditions (the boundary conditions on \( E_z \) and \( h^* \) are different on the access lines) to avoid the same location as the source and as the observation points.

The expression that allows to solve our problem and to find the electric field \( E_z \) everywhere inside the ferrite thin film is (with \( \tau \) the ferrite slab volume being bordered by the \( \sigma \) surface) is:

\[
E_z (x', y') = \int_{\tau} s(x, y)h^* (x, x', y, y') d\tau + \oint_{\sigma} (h^* \nabla E_z - E_z \nabla h^*) \cdot d\sigma (1)
\]
$h^*(x, x', y, y')$ is the adjunct Green’s function [6] defined by:

\[
h^*(x, x', y, y') = g(x', x, y, y') \tag{2}
\]

The volume integral (1) is applied to the ferrite slab volume with a possible source $s(x; y)$. However, using inhomogeneous boundary conditions, the final solution of the $E_z$ field is obtained without an internal source and the relation (1) becomes as follows:

\[
E_z(x', y') = \oint_{\sigma} (h^* \nabla E_z - E_z \nabla h^*) \cdot d\sigma \tag{3}
\]

The initial equation to find Green’s function in cartesian coordinates is given by:

\[
\left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k^2 \right) g = \delta (x - x') \delta (y - y') \tag{4}
\]

where $k = \omega \sqrt{\mu_0 \varepsilon_0 \varepsilon_{rf} \mu_{eff}}$ and $\mu_{eff} = \mu^2 - \kappa^2$ ($\mu$ and $\kappa$ are constitutive parameters of the ferrite permeability tensor).

The derivation of Green’s function (when a magnetic wall is fixed as a boundary condition along the ferrite slab) [6] leads to:

\[
g(x, y, x', y') = \sum_n -e^{j\alpha_n(x-x') \over 2a} \cdot \frac{\left( \begin{array}{c} \beta_n \cos (\beta_n (y' - b)) - \alpha_n \kappa \sin (\beta_n (y' - b)) \\ \beta_n \sin (2\beta_n b) \\ \beta_n \cos (\beta_n (y + b)) - \alpha_n \kappa \sin (\beta_n (y + b)) \end{array} \right)}{\left( \begin{array}{c} \beta_n^2 + \alpha_n^2 \kappa^2 \\ \beta_n^2 + \alpha_n^2 \kappa^2 \mu^2 \\ \beta_n^2 + \alpha_n^2 \kappa^2 \mu^2 \end{array} \right)} \bigg|_{y < y'} - \frac{\left( \begin{array}{c} \beta_n \cos (\beta_n (y' + b)) - \alpha_n \kappa \sin (\beta_n (y' + b)) \\ \beta_n \sin (2\beta_n b) \\ \beta_n \cos (\beta_n (y - b)) - \alpha_n \kappa \sin (\beta_n (y - b)) \end{array} \right)}{\left( \begin{array}{c} \beta_n^2 + \alpha_n^2 \kappa^2 \\ \beta_n^2 + \alpha_n^2 \kappa^2 \mu^2 \\ \beta_n^2 + \alpha_n^2 \kappa^2 \mu^2 \end{array} \right)} \bigg|_{y > y'} \tag{5}
\]

where $\alpha_n = {\pi n \over a}$ and $\beta_n^2 = k^2 - \alpha_n^2$.

From the integral relation (3) the $E_z$ field can be found on the access lines and the scattering parameters can be determined [7]. Figure 2 shows some results from this analytical model which
was slightly modified to take into account non perfect magnetic wall at the ferrite slab edge. Non reciprocal effects are observed since $S_{21}$ and $S_{31}$ are different from 40 to 45 GHz. These results are in agreement with 3D HFSS simulations which show a large effect in a wide frequency band (see the following paragraph) although some discrepancies are observed. However the model allows us to determine the length of the rectangle giving priority of the first mode:

$$a = \Re \left\{ \frac{\pi}{K} \sqrt{\frac{H_i}{\mu}} \right\} \quad (6)$$

Then, the width of the rectangle $b$ is determined by empirical means.

### 3. 3D SIMULATIONS

Now, the same structure is simulated by the HFSS 3D electromagnetic software. Many simulations were made with several parameters having varied. Figure 3 shows the results ($S_{11}$, $S_{21}$ and $S_{31}$) obtained from the same structure as on Figure 2(a). As we have already indicated: similar non reciprocal effects are observed that the ones found by the analytical model, on a wide frequency band around 40 GHz. However, there are some discrepancies between the results obtained from the HFSS and the analytical model simulations. For example, the bandwidth is larger than the one given by the analytical model. This phenomenon is all greater as the boundary conditions on the ferrite edge depart from a perfect magnetic wall.

![Figure 2: $S_{11}$, $S_{21}$ and $S_{31}$ of two different rectangular structures obtained from the analytical model with ferrite magnetization $M_s = 382$ kA/m; internal field $H_i = 1400$ kA/m and dimensions: (a) $a = 740 \mu m$ and $b = 300 \mu m$; (b) $a = 800 \mu m$ and $b = 500 \mu m$.](image_url)

![Figure 3: $S_{11}$, $S_{21}$ and $S_{31}$ of two different rectangular structures obtained from HFSS with ferrite magnetization $M_s = 382$ kA/m; internal field $H_i = 1400$ kA/m and dimensions: (a) $a = 740 \mu m$ and $b = 300 \mu m$; (b) $a = 800 \mu m$ and $b = 500 \mu m$.](image_url)
The three ports are not located in a symmetrical way. Thus, non reciprocal effects are not similar between two successive ports. For example, Figure 4 shows $S_{23}$, $S_{32}$ parameters part (a) and $S_{13}$, $S_{31}$ parameters part (b). This drawback could be overcome by a rigorous impedance matching.

The dimensions and the D.C. internal field are determined by using the analytical model, then the optimization is performed in making them vary separately. For example, the results obtained when the internal D.C. field value is 1000 kA/m are shown on Figure 5. Only small effects are observed and this D.C. value is not usable.

The best results are pointed out when the rectangle size is $740 \mu m$ by $300 \mu m$ and the D.C. field value is 1400 kA/m. The bandwidth value can reach 5 GHz and the relative bandwidth 10.5 per cent. Other parameter influence (access line width...) has been studied but not presented in this paper.

Therefore, important comments could be done: even if the impedance matching is quite wrong (the $S_{11}$ parameter is almost close to 1 everywhere), high non reciprocal effects are shown in a large frequency band. This structure could be used as “rectangular circulator”.

Figure 4: (a) $S_{23}$, $S_{32}$ parameters, (b) $S_{13}$, $S_{31}$ parameters for the same structure as on Figure 2 part (a).

Figure 5: $S_{11}$, $S_{21}$ and $S_{31}$ obtained for ferrite magnetization $M_s = 382$ kA/m and internal field $H_i = 1000$ kA/m, (a) from HFSS, (b) from the analytical model.
4. CONCLUSION

A rectangular junction ferrite component has been studied. It is made from a stripline structure including two ferrite slabs which are magnetized along the $z$-axis direction. Using a rectangular structure avoids the use of bent access lines that could disturb the TEM line propagation. According to the first results, the component must be improved before it is a rectangular circulator. The impedance matching must be performed. The analytical model could be better adjusted if we took into account non perfect boundary conditions used for Green’s function derivation.

Barium or strontium ferrites seem to be suitable to operate in millimeter waves. Thin film deposition requires high temperature annealing with a magnetic moment direction. Composite magnetic materials made from directed nano particles scattered into a host dielectric matrix constitute another interesting solution owing to their low temperature processes. This will true provided that the magnetic moment direction be maintained.

On the same way, other structures as coplanar and microstrip could be investigated.

Research domain of self-biased magnetic material still remains a challenge for integrating non reciprocal components.

REFERENCES