Design of a Coplanar hexagonal-shaped circulator based on ferrite film

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***Abstract*— In order to meet the needs of the telecommunications industry, it has become important to boost the effectiveness of devices due to the rapid development of microwave applications in recent years. In this paper, we have discussed the design and simulation of a 3-port hexagonal coplanar structure circulator that is made using the Yttrium Iron Garnet (YIG) film. A 3-dimensional finite element approach is used to analyze the design. The proposed circulator design is intended to work in the C band frequency range. The insertion loss attained is around 0.48 dB. The isolation attained is approximately around 24.36 dB whereas the return loss is approximately 20.64 dB.**

***Keywords*— circulator, YIG, S-parameters, FMR, ferrites, nonreciprocity, coplanar structure**

I. Introduction

RF and Microwave devices are being more commonly used in telecommunication networks. Different research is being done on circulators as well as isolators (non-reciprocal devices) in order to improve efficiency, minimize the size, reduce losses, improve the bandwidth, and these devices are subsequently deployed for usage. Circulators are used in systems that employ a single antenna for transmitting as well as for the reception. Their main purpose is to make it easier to route leaving & receiving signals to a proper transmitter or receiver [1].

Circulators isolate high- and low-power signals in full-duplex single antenna, transmitter, and receiver systems' broadcast and receiving channels. The circulator prevents high-power amplifiers from hazardous power reflections from the antennas during the transmission phase. During the reception phase, circulators route weak signals to an extremely sensitive power amplifier.

Ferrite circulators have evolved significantly from their modest beginning as a practical implementation of Faraday rotation some few decades back [2]. Because of the substantial growth in the telecommunications business, the advancement of non-reciprocal device types has drawn a lot of attention recently. Junction circulators built on ferrite, are typically utilized in current radar systems. Non - reciprocal features of biased ferrite circulators are highly appreciated in the «data transmission» module, wherein wireless signals are both intercepted and transmitted by a single antenna at about the same time & same frequency.

In 1962, Bosma published a paper on the stripline Y-junction circulator that was widely read. Through this investigation, it will be possible to determine the circulation conditions, thereby, deriving the critical physical parameters that will be used in the construction of stripline circulators[3].

The above-mentioned constraints can be solved by placing conducting components and the ground(GND) plane adjacent to the dielectric substrate. This type of integrated-circuits transmission line design is known as a coplanar waveguide (CPW).

A conducting metallic strip and two ground strips are concurrently positioned adjacent to something in the construction of a CPW, which would be formed on an insulating slab. This sort of transmission line lends itself to the production of integrated circuits (ICs)[4].

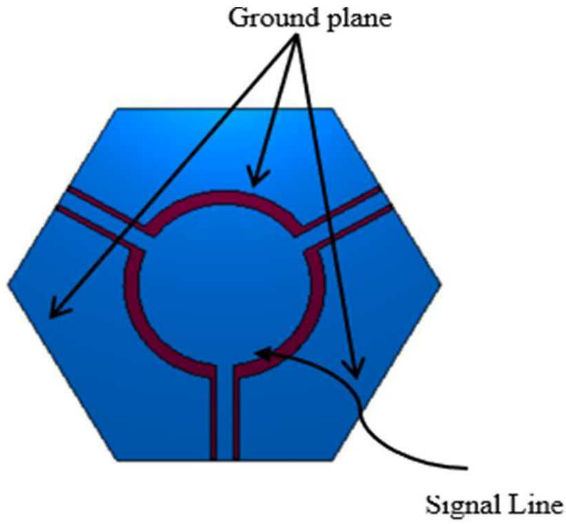

Fig. 1. Circulator based on Coplanar Waveguide structure

The Circulator that is having coplanar CPW structures are more intriguing in current technology, specifically with the push toward developing better and more efficient devices. There is a signal line & a GND that are in the identical plane in coplanar structures, and this is well suited to that of a monolithic microwave integrated circuit (MMIC). It can be observed that connecting the shunt to these electrical devices is very straightforward using CPW [5].

The following are some of the few benefits of a coplanar structure:

- With CPW conducting parts, also it is simple to interconnect a shunt to that of an electrical device.
- The installation of a ferrite disc does not necessitate the drilling of a-holes through all the base or substrate.
- Straightforward realizations as a result of one side's etching.
- Minimum dispersion

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These circulators have been developed using several well-known, but Strip line-specific approximation principles. As a result, prior to achieving a working coplanar circulator, its basic design should be optimized.

The microstrip Y-junction circulator is the device that is most typically utilized in these systems. Since 1962, Bosma has defined the operational principle based on a ferrite of a non-reciprocal Y- circulator, which is a non-reversible Y-circulator, which he first disclosed in 1962 [6].

Polder tensor is utilized in this analysis to characterize the tensor permeability of the ferrite, and it is defined as A circulator having a CPW structure, on the other hand, because both the line as well as the GND are positioned in the similar plane and therefore are straightforward to the pattern, it is well suited for microwave integrated circuit applications.

It was Wen [7] who was the first to investigate and create the theory of the CPW. In the following, Ogasawara [8] demonstrated and validated the point regarding the Y-junction circulators having CPW being capable of operating satisfactorily at specific frequencies. Many researchers have explored and developed circulators with a CPW configuration, which have since been implemented.

Zahwe [9, 10] put a lot of effort into researching and developing the given device.

Boyajian [6] suggested made of Hexaferrite nanocomposite, a circulator, which was accepted. Having a wordin our earlier paper, and of the circulator, the transmission characteristics were investigated using an Ansoft High-Frequency Simulation System.

Helszajn's et.al model [8,9] for the stripline structure is used to investigate the operation of such a circulator.

Later, in 2007, Zahwe conducted research on this sort of circulation [10]. Similar to a circulator stripline circulator, this machine works in much the same way. Making a micro circulator with YIG is one of the key objectives (ferrite of 1mm thick). A small insertion loss,a high isolation, and minimal reflection levels at most of the component's port locations are required for the development process.

II. THEORETICALICAL STUDY

A functional Y-junction stripline circulator's dimensions may be estimated using the design guidelines that Bosma's[11] theoretical conclusions enable. Green's function is used to express each component of the scattering matrix. Magnetic material properties, polarization, plus circulation frequency make up the design rule parameters [12]. Since it is assumed that the electric field strength in the disc has a z-component, the precise gyro tropic permeability is provided by the formula below[13].

$$||\mu|| = \{\begin{matrix} \mu & -ik & 0 \\ ik & \mu & 0 \\ 0 & 0 & 1 \end{matrix}\} \quad (1)$$

The components of ferrite materials' Polder tensors are κ and μ. In the above-given matrix, i is equal to $\sqrt{-1}$.

The Polder tensor i.e., μ_{eff}, which measures the effective permeability of ferrite, is described as:

$$\boldsymbol{\mu_{eff}} = \frac{(\mu^2 - k^2)}{\mu} \quad (2)$$

The ferrite films' internal field, Hi, is described by:

$$H_i = H_0 + H_a - N_z M_s \quad (3)$$

where Nz is known as the demagnetizing factor and Nz is equal to 1 for thin film, the saturation magnetization is represented by Ms, H0 is known as the external field, and the anisotropy field is given by Ha. It stands to reason for a thin film circulator that Nz=1 & H0=0, then:

$$H_i = H_a - M_s \quad (4)$$

III. DESIGN OF THE COPLANAR HEXAGONAL CIRCULATOR

A CPW circulator is a prominent contender for microwave integrated circuits, since the transmission line i.e. signal and metallic grounds are both positioned in the similar plane (usually both on the top).

This type of integrated-circuits transmission line design is known as a CPW structure[14].

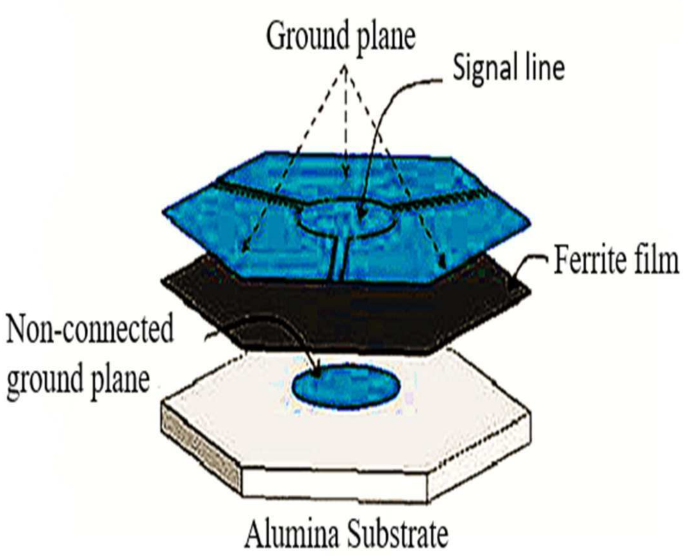

Fig. 2. Hexagonal Coplanar Circulator with different stages[9]

These conducting metallic strips and two ground strips are concurrently positioned adjacent in the construction of a coplanar-waveguide, which would be formed on an insulating slab. This sort of transmission line lends itself to the production of integrated circuits (ICs).

Figures 2 represent the CPW circulator structure's cross-sectional view showing different stages. The CPW's inner conductor and outer conductors are placed on one surface of the dielectric substrate. For the circulator to operate properly, a ferrite-based disc is placed on the Y junction of the inner conductor [15].

For the circulator to give its best performance in the required frequency band a patch is introduced around the ferrite thin film. As in frequency domain solver ferrite cannot be directly connected to the port because that is not supported in the port mode calculation. So, to avoid this issue in the frequency domain solver a mica patch around the thin ferrite film [16,17,18].

Fig 3 shows the mica patch around the YIG ferrite thin film with an epsilon of 7.9 and a height of 0.123 mm. it is having a radius of 0.05 mm outside the ferrite.

This patch will improve the return loss and insertion loss compared to vacuum instead of any other dielectric material.

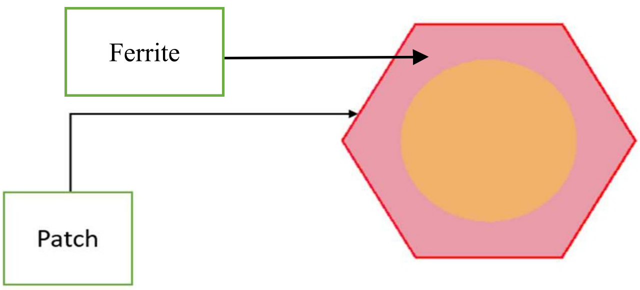

Fig. 3. A Thin layer of Mica patch around the ferrite film

Physical parameters for ferrite film, mica patch, conductor, and substrate used by the design discussed in the paper are listed below:

TABLE I. PARAMETERS OF THE DESIGN[8]

COMPONENT	MATERIAL	EPSILON (ϵ_R)	MU	HEIGHT (MM)
SUBSTRATE	ALUMINA	9.4	1	1.200
NONCONNECTED GROUND	COPPER		1	0.001
PATCH	MICA	7.9	1	0.123
GROUND PLANE	COPPER		1	0.0075

A Y-junction [19] and 3 ports each with an impedance of 50Ω make up the circulator. As shown in Figure 2, the CPW's signal line & GND are positioned on a matching plane over a YIG ferrite material with a 0.0065mm thickness (hf) as proposed by O. Zahwe in [9]. The height of ferrite is scaled by 1.8 to get the result for the desired frequency band. This ferrite film is placed on the substrate of alumina having a height of 1.200mm and a radius of 9.45 mm. Between Ferrite and substrate there lies a non-connected ground of thickness of 0.001 mm and a radius of 5.67 mm.

The internal bias field is expected to be consistent and also the ferrite is intended to be saturated. Between both the ferrite as well as the dielectric substrates, the bottom non-connected ground plane serves as a bridge for the field transitions between line accesses and the 3 center circulators. The YIG [20] layer is then subjected to a magnetic bias field (Hdc) that is given perpendicularly.

TABLE II. FERRITE MATERIAL PROPERTIES & DIMENSIONS [8]

Material	**YIG**
Epsilon	15.4
4π Ms (Gauss)	1746
ΔH (Oe)	15
Lande factor	2.01
Height of Ferrite(h_f)	0.123
radius	8.5
tan δ	0.0002

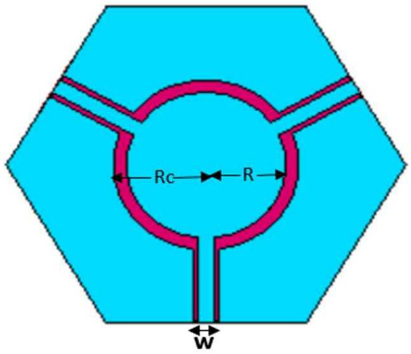

Fig. 4. Top view of the Coplanar circulator showing different parameters[9]

Using the CST Studio Suite [21], the design's geometry has been optimized. The Design frequency ranges from 5.2GHz to 6.4GHz. The measurements [22] (as shown in Figure 4) used for optimizing the design are given:

R= 3.6 mm (the "Signal Line" or central conductor's radius)

Rc= 4.194 mm (the radius for the non-connected plane)

S=0.234 mm (The Signal line (i.e., S)

W=0.72 mm (width of S)

IV. SIMULATION RESULTS

The hexagonal CPW circulator was created using the commercial software CST Studio suite. We investigated the impact of several factors on the circulator's performance. The transmission properties of the circulator were examined using this software, which uses a three-dimensional finite element approach.

The dielectric constant = 15.4, saturation magnetization (Ms) is 1746, resonance line width of 15 Oe, tan = 0.0002(i.e., dielectric loss tangent), and linewidth of 15 Oe have been used to simulate the YIG ferrite film. The YIG ferrite films have a perpendicular internal magnetic bias field applied to them.

In order to avoid the failure caused by anisotropic materials not been supported in port mode calculation, Ferrite film is not directly connected with the ports. Therfore two different method was adopted in order to optimize the design. The radius of ferrite film was reduced by 0.05mm so that it does not touch the port.

A. Simulation Results without patch around ferrite

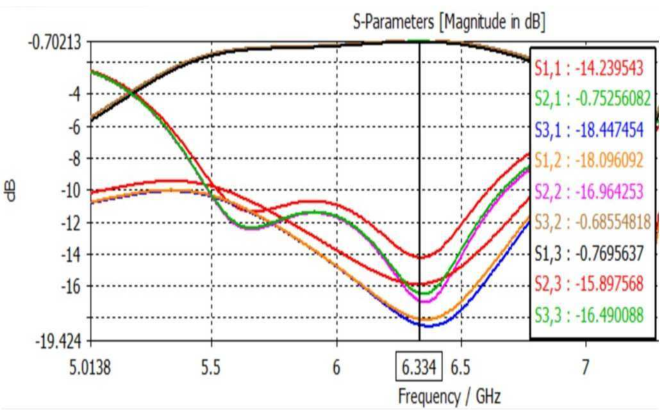

Fig. 5. S Parameter for the simulated hexagonal coplanar circulator without a patch around YIG ferrite film

The space was left empty in order to simulate the design. The simulation result was as such the maximum return loss obtained was17.02 dB, isolation loss was 18.49 dB and insertion loss of about 0.68 dB. The figure 6 shows the E-field at 6 GHz for the design without patch.

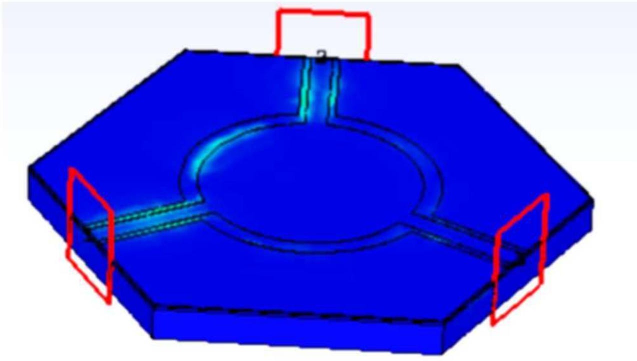

Fig. 6. E-field for design without patch

B. *Simulation Results with a mica patch around ferrite*

To reduce the losses a mica patch of radius 0.05 mm was introduced around the YIG ferrite film. The results obtained are shown in figure 7.

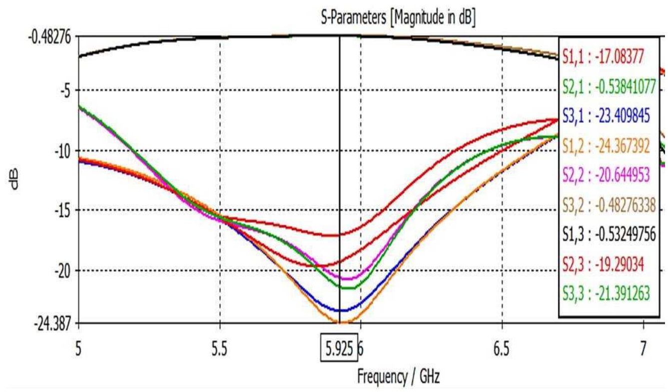

Fig. 7. S Parameter for the simulated hexagonal coplanar circulator with a mica patch around YIG ferrite film

The best isolation loss observed is 24.36 dB, return loss is 21.39 dB and insertion loss of 0.48 dB. The VSWR i.e., voltage standing wave ratio observed is nearly 1.22.Following figure shows the E-field for design without patch.

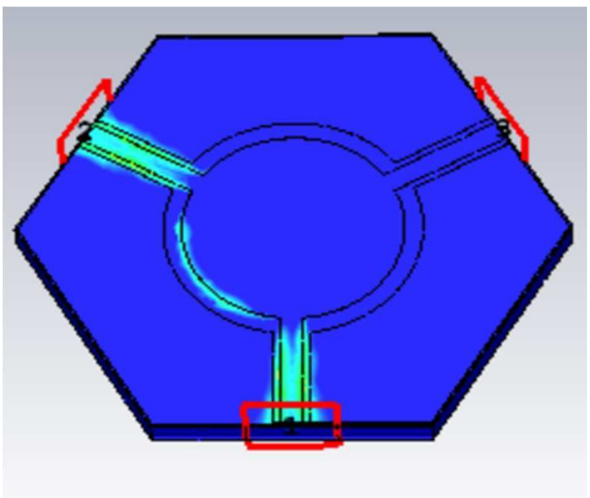

Fig. 8. E-field results for proposed design with mica patch

CONCLUSION

A hexagonal shaped coplanar circulator has been designed and simulated. Only a 0.122 mm thick YIG film ferrite was used for the design. 3D finite element software has been used to analyze of the presented design. Two permanent magnets made of nickel were used to magnetize ferrite. Two designs were compared one with mica patch around the ferrite and the other without the patch. It was seen that the design with mica patch gives good results compared to the other one. With an insertion loss level of 0.48 dB and an isolation of about 24.36 dB at the 5 GHz-6.34 GHz frequency range. The centre frequency is around 5. 9GHz. Return loss for the given design is nearly about 20.64 dB. Bandwidth is around 1.02 GHz and VSWR is nearly about 1.2. Although there isn't much ferrite material utilised inside the device, as well as the construction is perfectly compatible using low-cost industrial methods, this device and its features are nevertheless highly intriguing.

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REFERENCES

[1] Linkhart, Douglas K. Microwave circulator design. Artech house, 2014.

[2] Hong, Yang-Ki, and Jaejin Lee. "Ferrites for RF passive devices." In *Solid State Physics*, vol. 64, pp. 237-329. Academic Press, 2013.

[3] Bosma, "On stripline Y-junction at UHF," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-12, pp. 61-72, Jan. 1964.

[4] Fay, C. E., and R. L. Comstock. "Operation of the ferrite junction circulator." IEEE Transactions on Microwave Theory and Techniques 13, no. 1 (1965): 15-27.

[5] Kitajima, K., H. Nakano, K. Koshiji, and E. Shu. "Improvement in the Operating Bandwidth of Coplanar Waveguide Circulator." Journal of the Magnetics Society of Japan 22, no. S_1_ISFA_97 (1998): S1_360-362.

[6] H. Bosma, On the principle of stripline circulation, Proc. of The Institution of Electrical Engineers, London, Vol. 109, No. 21, 1962, 137-146.

[7] C. P. Wen, "Coplanar waveguide, a surface strip transmission line suitable for nonreciprocal gyromagnetic device applications," Microwave Symposium, 1969 G-MTT International, pp. 110–115, 1969.

[8] Ogasawara, N. and M. Kaji, "Coplanar-guide and slot-guide junction circulators," *Electronics Letters*, Vol. 7, No. 9, 220–221, May 6, 1971.

[9] O. Zahwe, B. Sauviac, and J. J. Rousseau, "Fabrication and measurement of a coplanar circulator with 65 μm yig thin film," Progress In Electromagnetics Research, vol. 8, pp. 35–41, 2009.

[10] O. Zahwe, B. Abdel Samad, B. Sauviac, J.-P. Chatelon, M. Blanc Mignon, J. Rousseau, M. Le Berre, and D. Givord, "Yig thin film used to miniaturize a coplanar junction circulator," Journal of Electromagnetic Waves and Applications, vol. 24, no. 1, pp. 25–32, 2010.

[11] H. Bosma, "On stripline Y-junction at UHF," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-12, pp. 61-72, Jan. 1964.

[12] E. Benevent, T. Rouiller, B. Sauviac, V. Larrey, D. Vincent, and A. Madelaine, "Stripline Y-junction circulator using barium hexagonal ferrite thin films," in Proc. of IEEE International Symposium on Industrial Electronics, Ajaccio, France, 2004, pp. 15-1

[13] Zahwe, Oussama, B. Abdel Samad, B. Sauviac, Jean-Pierre Chatelon, M. F. Blanc Mignon, J. J. Rousseau, M. Le Berre, and D. Givord. "YIG thin film used to miniaturize a coplanar junction circulator." *Journal of Electromagnetic Waves and Applications* 24, no. 1 (2010): 25-32.

[14] Zahwe, Oussama, Bruno Sauviac, Bassel Abdel Samad, Jean Pierre Chatelon, and Jean Jacques Rousseau. "Numerical study of a circulator

using YIG thin film with a coplanar structure." Progress In Electromagnetics Research C 6 (2009): 193-207.

[15] Free, Charles E., and Colin S. Aitchison. "Microwave Ferrites." (2022): 171-191.

[16] Fernandez, Cristina, Zoran Pavlović, Santosh Kulkarni, Paul McCloskey, and Cian O'Mathúna. "Novel high-frequency electrical characterization technique for magnetic passive devices." IEEE Journal of Emerging and Selected Topics in Power Electronics 6, no. 2 (2018): 621-628.

[17] Hong, Yang-Ki, and Jaejin Lee. "Ferrites for RF passive devices." Solid State Physics. Vol. 64. Academic Press, 2013. 237-32

[18] Zahwe, Oussama, Walaa Nasser, and Hassan Harb. "Analytical, Numerical and Experimental Study of an Original Design for a Coplanar Circulator/Isolator Based on Thick and Thin Ferrite Film." In

[19] 2018 International Arab Conference on Information Technology (ACIT), pp. 1-8. IEEE, 2018.

[20] Qassym, L., V. Laur, R. Lebourgcois, and P. Queffelec. "Ferrimagnetic garnets for low temperature co-fired ceramics microwave circulators." In 2018 IEEE/MTT-S International Microwave Symposium-IMS, pp. 750-752. IEEE, 2018.

[21] Solvers, Electromagnetic Simulation, and C. A. D. Compatibility. "CST Studio Suite." (2020).

[22] Zahwe, Oussama, Hassan Harb, and Hussein Nasrallah. "Design of acoplanar circulator based on thick and thin ferrite film." Int. Arab J. Inf. Technol. 16, no. 3A (2019): 600-608.