Наносистеми, наноматеріали, нанотехнології
Nanosistemi, Nanomateriali, Nanotehnologii
2023, т. 21, № 2, сс. 247–252

PACS numbers: 07.05.Hd, 75.50.Gg, 81.07.Oj, 84.40.Az, 85.70.Ge, 85.85.+j

Numerical Study of Passive Irregular Hexagonal Circulator with Coplanar Topology in the Band 7–10 GHz

A. Bahloul and A. Boualleg

Laboratory of Telecommunications,
Department of Electronics and Telecommunication,
Faculty of Science and Technology,
University of 8 May 1945,
24000-BP 401 Guelma, Algeria

This paper presents a new design of an irregular hexagonal circulator with coplanar topology. The proposed coplanar circulator has an irregular hexagonal central conductor operating at the low frequency of 7–10 GHz. Yttrium iron garnet (YIG) is used in this circulator as the magnetic material that confer the nonreciprocity. This structure is analysed by high-frequency structure simulator (HFSS), which is based on finite-element method, to check all nonreciprocal transmission characteristics at the operating frequency. The results obtained show a good agreement with those developed in the literature.

У роботі представлено нову конструкцію нереґулярного шестикутнього циркулятора з компланарною топологією. Запропонований компланарний циркулятор має неправильний шестикутній центральний провідник, що працює на низькій частоті у 7–10 ГГц. Залізоітрійовий ґранат (YIG) використовується в цьому циркуляторі як магнетний матеріял, який надає невзаємність. Ця структура аналізується симулятором високочастотної структури (HFSS), який базується на методі скінченних елементів, для перевірки всіх невзаємних характеристик передачі на робочій частоті. Одержані результати показують хороший збіг з розробленими в літературі.

Key words: circulator, *S*-parameters, yttrium iron garnet, nonreciprocity, waveguide, hexagonal structure.

Ключові слова: циркулятор, *S*-параметри, залізоітрійовий ґранат, невзаємність, хвилевід, шестикутня структура.

(Received 14 October, 2022; in revised form, 20 October 2022)

1. INTRODUCTION

The electromagnetic properties of magnetic materials are important for microwave passive component design. Isolators and circulators, which are nonreciprocal passive components, usually contain bulk ferrites [1]. This passive component known since the fifties is always subject of researches for the improvement of their performances and their miniaturization. These performances are characterized by the insertion loss, the isolation, the reflection and the length of the bandwidth. As a coplanar transmission line, coplanar waveguide (CPW) offers several attractive features; it is very suitable for microwave and millimetre wave components [2].

In the sixties, Bosma introduced the strip-line junction circulator [3, 4] and described the geometric and magnetic conditions for the good operation of this device.

In 1969, Wen [5] proposed the coplanar waveguide structure (CPW); Ogasawara and Koshiji [6] confirm that the design of the circulator with CPW structure give a good response at certain frequency. Other authors have studied the circulators for all models of microstrip [6] forms, strip-line [7] and coplanar [8, 9].

The planar junction circulator using an irregular hexagonal resonator has been proposed and studied by Helszajn [10] using a microstrip topology.

The purpose of this study is to propose and study numerically with the Ansoft HFSS (high-frequency structure simulator) the irregular hexagonal circulator with CPW topology operating at a band with a good performance.

2. DESIGN OF CIRCULATOR WITH CPW STRUCTURE

The design of our coplanar circulator having the hexagonal central conductor is based on the theory magnetic and geometric structure of Bosma [3] and Helszajn [10, 11] as shown in Fig. 1.

3. GEOMETRIC AND MAGNETIC RULES BY BOSMA

From the theoretical results obtained by Bosma [3], the circulation condition is defined by the following relations:

$$\frac{R}{\lambda} = \frac{\chi_{11}}{2\pi\sqrt{\varepsilon}}\sqrt{\frac{H_i}{H_i + 4\pi M_s}}, \quad (1)$$

$$\psi = \frac{1}{\sqrt{3}}\frac{\pi\,\kappa/\mu}{1.84\sqrt{\mu_{\text{eff}}/\varepsilon}}, \quad (2)$$

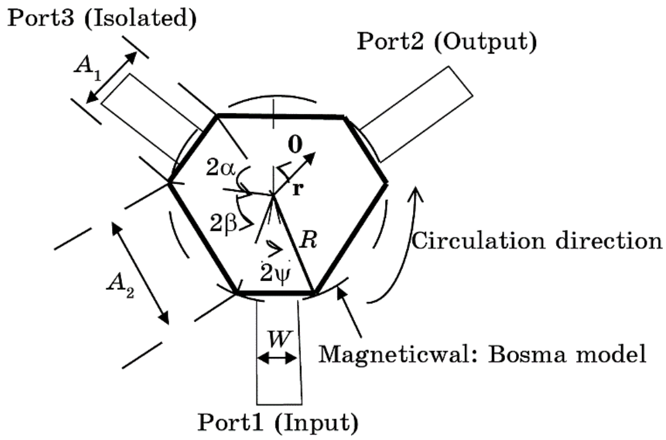

Fig. 1. Physical variables of irregular hexagonal circulator.

where R is the radius of the central disc conductor in the model by Bosma [3], ψ is a strip-line width angle, ε is the permittivity, χ_{11} is the Bessel's solution of the first resonance mode of the ferrite disks, μ_{eff} is the effective permeability of ferrite, and μ, κ are the polder tensor elements of ferrite materials.

It is possible to determine the strip-line conductor width W as a function of the strip-line width angle ψ and the circumscribed radius of an irregular hexagonal one R as follows [9]:

$$W = 2R\cos(\alpha)\tan\psi\,. \tag{3}$$

In the proposed device, the central conductor has been modified from a circular shape to an irregular hexagon shape as shown in Fig. 1. The sides A_1, A_2 of the irregular hexagon can be calculated using the following equations [9]:

$$A_1 = 2R\sin(\alpha)\,, \tag{4}$$

$$A_2 = 2R\sin(\beta)\,, \tag{5}$$

where α, β are the shape angles of a hexagon, where $\beta = 60^\circ - \alpha$.

The internal bias filed in layer of the ferrite is given by

$$H_i = H_0 + H_a - N_z M_s\,, \tag{6}$$

where H_0 is the external field, M_s is the saturation magnetization, N_z is the demagnetizing factor ($N_z = 1$ for a thin film), and H_a is the anisotropy field. For self-biased film circulator, it is reasonable that $H_0 = 0$ and $N_z = 1$; then,

$$H_i = H_a - M_s . \quad (7)$$

4. CIRCULATOR STRUCTURE

The circulator with a coplanar waveguide (CPW) proposed in this paper is shown in Fig. 2. The central part of our device has a hexagonal irregular pattern. This Y-junction circulator has three accesses oriented at 120° relative to each other.

The circulator is made with a thin YIG-ferrite film to confirm the nonreciprocal operation; its thickness is of around 100 μm (Fig. 4). This magnetic thin film is deposited over a 635 μm thick dielectric alumina (Al_2O_3) substrate, and the inferior ground of the irregular hexagonal is located between the ferrite and the dielectric substrate. Finally, signal line and ground plane are placed in an identical plan with a small slot (G_1) between line and GND as shown in Fig. 3.

The metallization of 1 μm thickness is made of a copper, which has a relative permeability $\mu = 0.9999991$ and a conductivity $\sigma = 58.106$ S/m.

The magnetic characteristics of the thin YIG films are: the relative permittivity $\varepsilon_r = 15.3$, the dielectric loss tangent $\tan\delta = 10^{-4}$, the

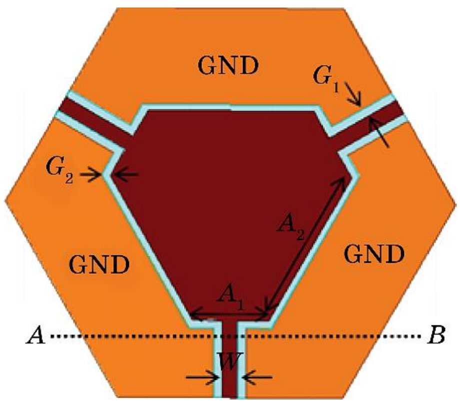

Fig. 2. Top view of CPW hexagonal circulator.

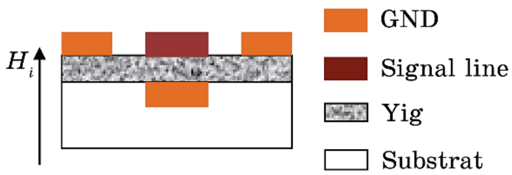

Fig. 3. Cross sectional view *AB* of CPW hexagonal circulator.

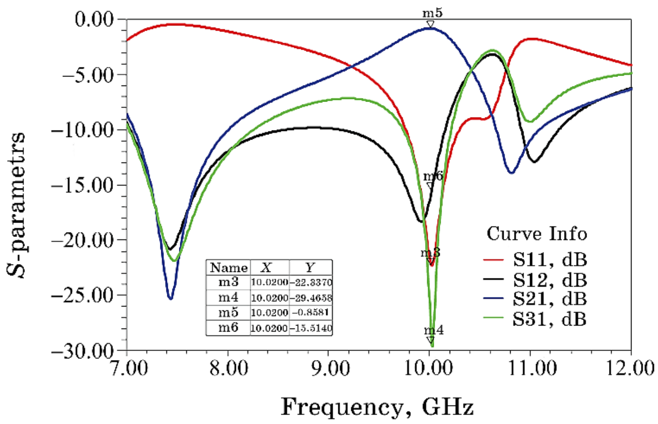

Fig. 4. Evolution of *S*-parameters of irregular hexagonal circulator with 100-µm YIG ferrite.

saturation magnetization $M_s = 1.780$ T, the ferromagnetic resonance line width $\Delta H = 100$ Oe at a frequency of 10 GHz, and the internal magnetic bias filed $H_i = 557000$ A/m has been applied in a perpendicular direction to the YIG ferrite.

5. SIMULATION AND DISCUSSION

The simulated *S*-parameters of the circulator are shown in Fig. 4. The nonreciprocal transmission characteristics are found at 10.2 GHz, with insertion loss S_{21} of −0.85 dB, the isolation S_{31} is of −29.46 dB, and the return loss is of about −22.33 dB.

The optimal dimensions corresponding to the obtained results of the circulator are: $W = 450$ µm (the width of the signal line), $G_1 = 50$ µm (the spacing between the signal line and ground plane), $G_2 = 20$ µm (the distance between the ground plane and the central conductor), and A_1, A_2 are the sides of the hexagonal conductor, which are equal to 1032 µm and 2827 µm, respectively. With these dimensions, the characteristic impedance is equal to 46 Ω.

6. CONCLUSION

In this work, the structure of irregular hexagonal circulator with coplanar topology is proposed and studied numerically with the Ansoft HFSS. All the geometric parameters of this circulator can affect directly on the transmission characteristics and the operating frequency. After the optimization of our circulator, the best performance is obtained around a frequency of 10 GHz with 100 µm of ferrite thickness.

The result appears that we are enhanced the irregular hexagonal circulator to function at a low-frequency band of 7–10 GHz with miniature simple topology and supernonreciprocal transmission characteristics.

REFERENCES

1. D. Vincent, T. Rouiller, C. Simovsky, B. Bayard, and G. Noyel, *Journal IEEE Trans. on Microwave Theory and Techniques*, **53**, No. 4: 1174 (2005); doi:10.1109/TMTT.2005.845730
2. T. Zahou, *Etude de Composants Passifs Hyperfréquences a Base de Métamatériaux et de Ferrite* [Study of Passive Microwave and Millimetre Wave Components Based on Matematerials and Ferrite] (Ph.D. Thesis) (L'institut National des Sciences Appliquées de Lyon: 2012); https://theses.hal.science/tel-00782328
3. H. Bosma, *The Institution of Electrical Engineers January*, **137**: 146 (1962).
4. H. Bosma, *IEEE Transactions on Microwave Theory and Techniques*, **12**, Iss. 1: 61 (1964); DOI: 10.1109/TMTT.1964.1125753
5. C. P. Wen, *IEEE Transactions on Microwave Theory and Techniques*, **17**, No. 12: 1087 (1969); doi:10.1109/TMTT.1969.1127105
6. C. E. Fay and R. L. Comstock, *IEEE Transactions on Microwave Theory and Techniques*, **13**, No. 1: 15 (1965); doi:10.1109/TMTT.1965.1125923
7. E. Benevent, T. Rouiller, B. Sauviac, V. Larrey, D. Vincent, and A. Madelaine, *Proc. of IEEE International Symposium on Industrial Electronics*, **15**: 18 (2004).
8. O. Zahwe, B. Sauviac, B. A. Samad, J. P. Chatelo, and J. J. Rousseau, *Progress in Electromagnetics Research*, **6**: 193 (2009); doi:10.2528/PIERC09020302
9. R. El-Bouslemti, F. Belkhodja, D. Vincent, and R. Naoum, *IOSR Journal of Electronics and Communication Engineering (IOSR–JECE)*, **31**: 37 (2013).
10. J. Helszajn, M. McKay, and D.J. Lynch, *IEE Proc. Microw. Antennas Propag.*, **532**: 538 (1996).
11. J. Helszajn, D. S. James, and W. T. Nisbet, *IEEE Transactions on Microwave Theory and Techniques*, **27**, No. 2: 188 (1979).