Multiband isolator based on a coplanar metaline

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Abstract
This study presents for the first time the feasibility of a coplanar isolator using YIG material for applications in the Ku, K and Ka bands. The proposed structure is an asymmetric coplanar waveguide with a transverse array of unopened slots etched on a ground plane. Such structures are characterized by several cut-off frequencies on the transmission parameters. With a low dc magnetic field of 72 kAm\(^{-1}\) applied along with the slots, significant nonreciprocal effects greater than 20, 19 and 29 dB are obtained at 13.95, 23.39 and 39.61 GHz, respectively. The proposed structure can be used as a multiband isolator for microwave applications. The low biasing field of this multiband isolator and its compactness (88 mm\(^3\)) are its main advantages, which makes this structure particularly suitable for integration.

1 | INTRODUCTION

Microwave devices are mainly used in radar and telecommunication systems. The needs of these modern telecommunication systems are in rapid growth so that engineers and researchers are required to develop low-cost, compact and lightweight devices operating at higher frequencies. Microwave ferrite components (isolators or circulators) are thus subject to research aimed at their miniaturization and their integration. Their basic operating principles can be explained by one or more of the following nonreciprocal effects in magnetized ferrites: Faraday rotation [1], gyromagnetic resonance [2], field displacement [3], spin waves, or magnetostatic waves [4].

Historically, the first ferrite components to be developed are Faraday isolators in waveguide technology [1]. A major drawback of Faraday isolators is linked to their bulky size which does not allow their implementation in microwave integrated circuits (MIC). Planar technologies offer a multitude of advantages over other technologies. For this reason, the investigations are more and more focused on planar structures. In the particular case of coplanar waveguide structures, the advantages are: simplicity of design, low-cost manufacturing, the possibility of integration of discrete elements, compatibility with MIC technology etc.

An isolator is a non-reciprocal passive component that allows the electromagnetic wave to propagate in only one direction. It is thus characterized by a low-loss transmission in the forward direction and very high isolation in the reverse one. Its interest is to prevent the propagation of the reflected signals caused by the mismatch between the different modules of a transmission system. Another way to obtain an isolator is to terminate one of the three ports of a circulator with a matched load.

Several configurations of planar isolators exist principally in stripline [5], slotline [6] or microstrip [3]. In coplanar technology, research has been initiated by Wen who first realized a coplanar isolator with rods of magnetic material located in the gaps of a coplanar waveguide [2]. Another configuration using a thinner ferrite material is presented in [4]. The literature also mentions some research on isolators based on substrate integrated waveguide (SIW) technology [7, 8]. The performances of some isolators related to the recent literature have been presented and summarized in Table 1.

Although many works have been reported on isolators using YIG material at X and Ku bands [4, 7, 8, 10], very little information can be found about planar isolators at K and Ka bands. Indeed, garnets are generally used between L and X bands [11]. However, an isolation ratio of 25 dB around 45 GHz was observed by Tsustsumi [12] using a slotline structure based on 100-μm-thick YIG film, but the insertion loss obtained is significant (20 dB). On the other hand, spinels could find application up to Ka band [11, 13, 14]. Other materials are also used to design and fabricate isolators such as magnetic nanowires [15] or semiconductors [16].

The rise in frequency and the increase in the number of communication standards require the design of multiband or
TABLE 1  Performance comparison of the existing designs in the recent literature

| Related works | Frequency (GHz) | Isolation (dB) | Insertion loss (dB) | Applied field (Oe) | Size (mm²) | Ferrite | Technology |
|---------------|----------------|---------------|---------------------|--------------------|------------|---------|------------|
| [9]           | 17.57          | 11.6          | 5.78                | 3500               | --         | NiZn    | HIW-Microstrip |
| [7]           | 9.81–10.24     | 30–55         | 1.1–2.2             | 2630               | 22.6×8     | YIG     | SIW        |
| [8]           | 13.5–16        | 17–30        | 2–5                 | 4000               | ≈ 39.2×12  | YIG     | SIW        |
| [10]          | 13.5           | 19.3          | 3.5                 | 4000               | ≈ 22×9     | YIG     | HIW-Microstrip |
| [4]           | 10.6           | 17            | 1                   | 2260               | 10×4       | YIG     | CPW        |

broadband component. For this purpose, a new multiband coplanar isolator with metamaterials such as high impedance wire (HIW) [17, 18] is proposed. The used technique is to achieve periodic resonant frequencies on the transmission through a planar transmission line based on a magnetic substrate and make it non-reciprocal by the application of an external magnetic bias field. Thus, this structure exploits the non-reciprocal properties of magnetic ferrites as well as those of metamaterials.

In this letter, an asymmetric coplanar isolator based on Yttrium Iron Garnet (YIG) material that can operate in Ku, K and Ka frequency bands, under a low dc magnetic field is presented for the first time. Experimental measurements of the scattering parameters are discussed and compared to the simulation results. This multiband coplanar isolator is suitable for microwave integrated devices.

2  | HIW ON COPLANAR FERRITE SUBSTRATE

2.1  | Design structure

A HIW can be obtained by means of identical resonant circuits interconnected in series [17]. A practical realization of this type of line is to implement serial slotline stubs on a coplanar line. These stubs which act as quarter-wave resonators are located on one of the ground planes of the CPW. For this asymmetric CPW isolator, the isolation function is obtained by combining the effects of the metaline with those of the ferrite biased with a constant magnetic field \( H_{DC} \).

The design parameters of the HIW are: the length of the stub \( (p) \), the width of the slot \( (g) \) and the period of the array \( (d) \). The parameter \( g \) must be very small compared to the wavelength and the period \( d \) smaller than the length \( p \) so that the designed medium can be seen by the traveling wave as a homogeneous material (metamaterial).

For the realization of the prototype, a thin copper layer of 3-\( \mu \)m thick is first deposited by radio frequency sputtering onto a 1 mm-thick polycrystalline YIG substrate. The length and the width of the substrate are 8 and 11 mm, respectively. Then, the lift-off technique is used to reproduce the host transmission line and the array of slots on the ground plane (Figure 1). The number of slots is 35 and all the geometric parameters of the design are given in Table 2. The fabricated prototype is shown in Figure 2.

2.2  | Origin of the nonreciprocal effect

In a conventional CPW, the current flows along the Z axis, essentially on the edges of the conductors. The resulting magnetic field has two dominant components \( H_x \) and \( H_y \). However, the presence of the slots on the ground plane forces the current to change direction (Figure 3), which results in a rotating magnetic field with \( H_x \) and \( H_y \) components. When the dc magnetic bias field is applied along the x-axis, the magnetic field is characterized by either a right-handed circular polarization (RHCP) or a left-handed circular polarization (LHCP) in terms of the dc magnetic bias field or magnetization [9, 10] (Figure 4). It is well known that the interaction of a magnetized ferrite with a circularly polarized wave depends on the direction of propagation [19]. So both the propagation and

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**FIGURE 1**  (a) The front view of the HIW on coplanar ferrite substrate, (b) layout of the asymmetric coplanar isolator

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**TABLE 2**  Geometric parameters of the asymmetric coplanar isolator
TABLE 2  Dimensions of the structure

| Design parameters | Dimensions | Design parameters | Dimensions |
|-------------------|------------|-------------------|------------|
| L                 | 5.1 mm     | W                 | 0.4 mm     |
| P                 | 4.7 mm     | S                 | 0.2 mm     |
| h₁                | 1 mm       | D                 | 0.2 mm     |
| h₂                | 3 μm       | G                 | 15 μm      |

![Photograph of fabricated HIW-CPW isolator](image)

**FIGURE 2**  Photographs of the fabricated HIW–CPW isolator: (a) metal coplanar isolator prototype and (b) device to be characterized with a probing system.

Attenuation constants of the forward propagation are different from those of the backward direction, leading to a nonreciprocal behaviour of the structure. It should also be noted that the metallization thickness can probably have an influence on the nonreciprocal properties of the coplanar isolator [20].

A ferrite material saturated with a transverse static magnetic field is characterized by a permeability tensor given by the Polder model [21]. When biasing the ferrite material, the off-diagonal terms are no longer equal. Thus, the anti-symmetric tensor will introduce two different propagation constants according to the direction of propagation of the microwave signal.

Inside the slots, the standing wave is the sum of the incident and reflected waves propagating along the X axis. When the length of the stub is equivalent to an odd multiple of a quarter of the guided wavelength, these two waves are in quadrature phase and a resonance peak appears. The resonance frequencies are given by the following expression:

\[
f_c \approx (2m + 1) \frac{c}{4p\sqrt{\mu_{\text{eff}}\varepsilon_{\text{eff}}}}
\]

where \(m\) is a natural number, \(c\) is the velocity of light, \(\mu_{\text{eff}}\) and \(\varepsilon_{\text{eff}}\) are the effective permeability and permittivity of the medium associated with the slot array, respectively. As the effective permeability of the magnetized ferrite depends on the direction of rotation of the circular polarization, the resonance frequencies in the forward direction are different from those of the opposite direction. This results in a nonreciprocal propagation through the structure.

**FIGURE 3**  The direction of the current flowing on the coplanar structure indicated by the red line.

![Diagram of LHCP and RHCP](image)

**FIGURE 4**  LHCP and RHCP of microwave magnetic field: (a) forward input and (b) reverse input.

A complementary viewpoint on the behaviour of the structure concerning the coupled-slots can be cited using the normal-mode method, as opposed to the coupled-mode method. Indeed, the coupled-mode method is only used in the case of weak coupling [22], that is, for a weakly magnetized ferrite. However, Teoh and Davis [23] proposed a normal-mode approach which is more accurate because no assumptions are made about coupling strength. They explained the behaviour of the axially magnetized ferrite-coupled lines as the superposition of right- and left-hand side circularly or elliptically polarized normal modes.

3 | SIMULATION AND EXPERIMENTAL VERIFICATIONS

3.1 | HFSS simulations

An analytical study of an HIW-coplanar structure based on ferrite material taking into account the couplings between the different slots is rather complicated. A circuit model based on transmission lines formalism could be proposed as in [17], then using the method presented in [24] the couplings between resonators could be included. But, the complexity of the problem would require the use of numerical simulation tools to obtain the coupling coefficients between each pair of resonators. In this context, we chose to only perform numerical simulations of the HIW–CPW isolator, which were carried out using Ansoft HFSS software [25] to analyse the scattering parameters (S-parameters). This 3D electromagnetic simulation...
software allows the definition of gyromagnetic materials and uses the Polder model to calculate permeability tensor. The design and material parameters for the numerical simulation are chosen to be roughly consistent with the experimental study.

The model used by HFSS for simulation is shown in Figure 5. To simulate the design, two excitation ports must be defined at both ends of the CPW. The dimensions of the waveport are chosen appropriately to be able to obtain a good excitation. For this study, waveport excitations were used to analyse the scattering parameters.

Simulations were performed in the K band and the transmission parameters obtained in this frequency band are shown in Figure 6. The insertion loss of 1.1 dB at 22 GHz for forward propagation ($S_{21}$, LHCP) and isolation of 18.1 dB for backward ($S_{12}$, RHCP) were observed; the corresponding non-reciprocal effect at this frequency is 17 dB. In this case, the coupling of RHCP waves and YIG material would be strong, while LHCP waves would have weak couplings. At 23.6 GHz, there is an additional side lobe due to the edge effect from the interconnection [10]; an opposite insertion loss of 2.1 dB and isolation of 16.7 dB characteristics were observed. The simulation results were obtained with an internal magnetic field of 80 kAm$^{-1}$.

The same phenomenon was observed in Ku band and is presented in Figure 7. Indeed, two non-reciprocal effects (9.6 and 6 dB) appear. The first resonance peak is observed at 12.8 GHz and the second at 15.3 GHz, with insertion losses of 0.9 and 3.8 dB, respectively.

### 3.2 | Measurement results

In this section, experimental results will be given and compared to the simulation results. The measurements were performed using the vector network analyser (A37397 Anritsu) and a probing system.

Figure 8 shows the transmission parameters measured at frequencies up to 40 GHz for a coplanar isolator based on YIG material. A low transverse de magnetic field of 72 kAm$^{-1}$ generated by an electromagnet was applied to the structure.

The cutoff frequencies obtained in the forward propagation corresponding to the expression (1) are 13.95 GHz ($m = 1$), 23.39 GHz ($m = 2$), 31.51 GHz ($m = 3$) and 39.23 GHz ($m = 4$). In the backward propagation, the frequencies observed are 13.05 GHz ($m = 1$), 22.41 GHz ($m = 2$), 31.99 GHz ($m = 3$) and 39.61 GHz ($m = 4$). On the other hand, we should have found two other resonance peaks ($m = 0$) in backward and forward propagation at 4.35 and 4.65 GHz, respectively. However, we obtained a cutoff frequency at 2.37 GHz. This is probably due to the gyromagnetic resonance of the YIG material which is around 4 GHz, modifying the value of the permeability in this range of frequencies.

The transmission parameters ($S_{11}$ and $S_{21}$) measured in the K band are shown in Figure 9. At 22.41 GHz, the insertion loss ($S_{21}$, LHCP) and isolation ($S_{12}$, RHCP) are 5.4 and 18.2 dB, respectively. Furthermore, a sidelobe appears at 23.39 GHz with an opposite insertion loss and isolation of 2.9 and 22.3 dB, respectively. The non-reciprocal effect (19.4 dB) obtained at this frequency is significant. This sidelobe is due to the edge effect as already mentioned in the simulation part. It should be noted that the experimental results obtained are in good agreement with the simulation results. However, a slight frequency shift and a difference in amplitude between the two results are observed, which can be explained by the non-
uniformity of the magnetic field applied in the experimental case. Figure 9 also shows that in the operating range of the isolator around 23.39 GHz, the return losses of both the forward \((S_{11})\) and backward \((S_{22})\) transmission are about \(-16.5\) and \(-13.6\) dB, respectively. This indicates that the missing energy was dissipated in the YIG substrate or radiated instead of reflecting back. For the second lobe, they are less than \(-10.4\) dB \((S_{11})\) and \(-13.2\) dB \((S_{22})\) around 39.23 GHz. These reflection coefficients can be enhanced by tapering the CPW to improve the matching.

4 | CONCLUSION

We have designed, fabricated and characterized a compact, lightweight and multiband isolator for applications in Ku, K and Ka bands. The structure is performed from a coplanar HIW printed on YIG substrate. Under the low magnetic bias field of 72 kAm\(^{-1}\), significant non-reciprocal effects of about 20.7, 19.4 and 29.4 dB were achieved at 13.95, 23.39, and 39.61 GHz, respectively. Simulation and experimental results are reasonably in good agreement and can be considered as one of the best performances obtained for YIG isolator operating in this frequency range. This proposed multiband isolator offers the possibility to develop low-cost components and can be easily implemented in MIC.

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