Effects of Realistic Magnetic Field in Ferrite on the Waveguide Circulator for Industrial Applications

Kaviya Aranganadin[1], Hua-Yi Hsu[2], and Ming-Chieh Lin[1*]

[1]Multidisciplinary Computational Laboratory,
Department of Electrical and Biomedical Engineering,
Hanyang University, Seoul 04763, Korea

[2]Department of Mechanical Engineering,
National Taipei University of Technology
Taipei 10608, Taiwan

*Contact Author Email: mclin@hanyang.ac.kr

2022 23rd International Vacuum Electronics Conference (IVEC) | 978-1-6654-4325-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/IVEC53421.2022.10292399

Abstract: *Industrial rectangular waveguide circulators (WR340), with narrow bandwidths of 50 MHz, are available in markets for a hefty price tag depending upon the frequency range. This paper focuses on designing a partial height ferrite circulator with a homogeneous applied bias field to achieve a wider operating bandwidth of 210 MHz. With the frequency centered at 2.45GHz, insertion loss less than 0.24 dB, reflection, and isolation better than 20 dB can be achieved. The circulator studies usually consider a homogeneous applied bias field to the ferrite in simulation, but this is not the case in actual products where permanent magnets are used to produce the magnetic field to ferrites. Hence, we implement a self-consistent model that provides a non-homogeneous applied bias field to the ferrite to show the importance of considering a realistic magnetic field in the simulation of ferrite waveguide circulators. The design and development are performed using the finite element method (FEM) simulations. In the self-consistent model that applies a non-homogeneous bias field, a bandwidth of from 100 MHz to 170 MHz can be achieved with some geometric modifications from the former design, highlighting the importance of considering a realistic magnetic field.*

Keywords: Microwave circulator; self-consistent modeling; non-homogeneous; FEM.

Introduction

A microwave circulator is a passive non-reciprocal 3 or 4 port device. A microwave or radiofrequency (RF) signal entering at any port is transmitted to the next port in a rotation. A port is an external waveguide that connects to the device. The ferrite circulator can be broadly classified into two main categories: 4-port waveguide circulator based on Faraday rotation of wave propagation and 3-port y-junction circulators based on cancellation of wave propagation over two different paths. The circulator has three main figures of merit: transmission, reflection, and isolation. This non-reciprocity behavior of the circulator can protect the oscillators from the damage of the reflected power from a load such as in plasma or material processing systems. It can also be used to separate the transmitted, and the received waves in radar or communication. The general design of a 3-port ferrite waveguide circulator aims at a low loss, higher transmission, high power but with limited bandwidth coverage. The industrial WR340 circulators operating in the s-band region (2.45 GHz) have a bandwidth of 50 MHz. The literature survey showed that an S-band waveguide circulator's modeling and simulation considered only an electromagnetic design where a homogeneous applied bias field is assumed for ferrite. In reality, this assumption fails as permanent magnets are used to produce the magnetic field that's non-homogeneous in nature and causes a difference in predicted values. This research studies detailed modeling and simulation of the self-consistent design that simulates a magnetic circuit for a circulator using permanent magnets in a magneto-static study that produces a non-homogenous applied bias field to the ferrite linked with the electromagnetic study of the circulator. The magnetic circuit was designed to construct a real-time prototype, and the magnetic field is adjusted by optimizing the geometry such that we obtain the central frequency at 2.45 GHz.

Model and Simulation Results

The circulator model consists of three rectangular ports connected with a chamfer at the center, where the ferrite is mounted on the aluminum stage. The metal discs made up of aluminum (radius*height = 2.5 cm*1 cm) are attached to the center of chamfer to hold the ferrite. The ferrite material is aluminum garnet of grade G-610 that has a magnetic saturation of 680 Oe, the linewidth of 40 Oe, and relative permeability of 14. The model assuming a homogenous magnetic field with some fine-tuning to geometrical parameters such as the shape of chamfer to be circular and partial height ferrites (radius*height = 1.925 cm*0.5 cm) with air gap of 1.33 cm between them gives a larger and wider operating bandwidth of about 210 MHz from 2.34 GHz to 2.55 GHz at -20 dB with its operating frequency centered at 2.45 GHz. Through optimization techniques and by applying a homogenous bias field of 100 Oe or 7.91 kA/m achieved 95.74% of transmission at the peak frequency of 2.45 GHz, as shown in Table 1. The model considering a non-homogeneous magnetic field uses a magneto-static solver for calculating permanent magnets and iron in a hollow aluminum disc of inner thickness of 0.5 cm. The magnets used in the simulation were Neodymium magnet (NdFeB) of grade N-35, which has a remanence (Br) of 1.230 mT, and Coercivity (Hc) of 869 kA/m, which is commonly available in markets. The magnet has a radius of 2 cm and a height of 0.28 cm, which was optimized to give a magnetic field that can produce a bandwidth centered at 2.45 GHz in the circulator.

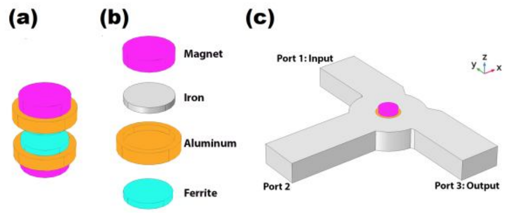

Figure 1: Schematics of (a) magnetic circuit, (b) disassembled parts of the magnetic circuit, and (c) WR340 circulator with the magnetic circuit in the FEM simulation.

Table 1. Performance of the WR340 circulator with homogenous and non-homogenous applied bias fields.

Case			Bandwidth @-20 dB GHZ	CF GHz	Transmission efficiency	
Field	MH cm	AR cm			Avg. %	@2.45 GHz %
Homogeneous	0.28	2.5	2.34 -2.56 =220 MHz	2.45	~95	95.7
*Case A	0.28	2.5	-	2.44	-	93.6
*Case B	0.56	2.5	2.44 -2.61 = 170MHz	2.54	~93	92.49
*Case C	0.56	2.72	2.36 -2.54 = 190 MHz	2.45	~93	94.17
*Case D	0.28	2.5	2.44 -2.53 = 90 MHz	2.49	~93	93.56
*Case E	0.28	2.6	2.4-2.51 =110 MHz	2.45	~93	94.29

*Here MH = magnet height, AR = Aluminum radius, CF = center frequency, Avg. = average bandwidth and, * for Non-homogeneous cases.*

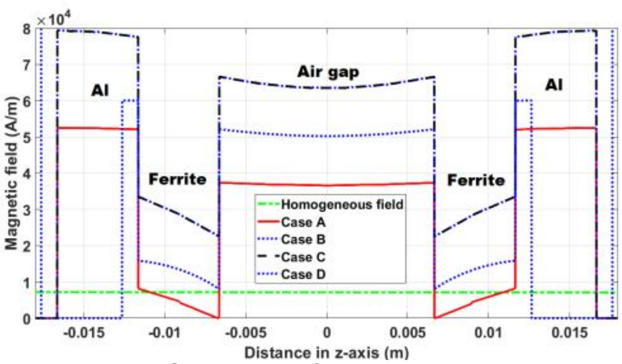

Figure 2: Comparison of homogenous and non-homogenous bias fields.

The realistic magnetic field obtained from the magneto-static solver is then passed as an applied bias field to obtain the ferrite tensor matrix in the electromagnetic solver. This introduces the non-uniform magnetic field in ferrite, as shown in Fig.2, leading to a self-consistent solution. From Table 1, a self-consistent model for the same circulator design does not produce a bandwidth at -20 dB, but the frequency is centered at 2.45 GHz, as shown in case A of Table 1, which is very different from the 210 MHz bandwidth predicted by the homogeneous model, thus exhibiting the importance of this approach. Here, the magnetic field across the ferrite region is inadequate to reach magnetic saturation, shown as the red line in Fig.2.

The magnetic field to the ferrite can be enhanced in two ways. One is to increase the size of magnets and the other is to reduce the thickness of aluminum. By following the first method, the height of the magnet was increased to 0.56 cm. This increases the magnetic field across ferrite, shown as the blue line in Fig.2. This increase in the magnetic field shifts the center frequency to 2.54 GHz, as predicted during the optimization study, but it gives a bandwidth of about 170 MHz with a transmission efficiency of > 93% while 92.49% at 2.45 GHz, as shown in case B of Table 1. During the optimization study, it is found that the frequency can be shifted by changing the radius of the aluminum metal stage in the circulator. Hence, the aluminum radius was changed from 2.5 cm to 2.72 cm to shift the frequency back to 2.45 GHz, giving a bandwidth of 190 MHz with 94.17% at 2.45GHz, as shown in case C of Table 1.

By following the second method to reduce the inner thickness of aluminum from 0.5 cm to 0.1 cm, a bandwidth of 90 MHz from 2.36 GHz to 2.54 GHz with a frequency centered at 2.49 GHz, and 93.56% as shown in case D of Table 1. By changing the aluminum radius to 2.6 cm, the frequency is shifted back to 2.45 GHz with 94.29% and a bandwidth coverage of 110 MHz with a transmission of 93%, as shown in case E of Table 1.

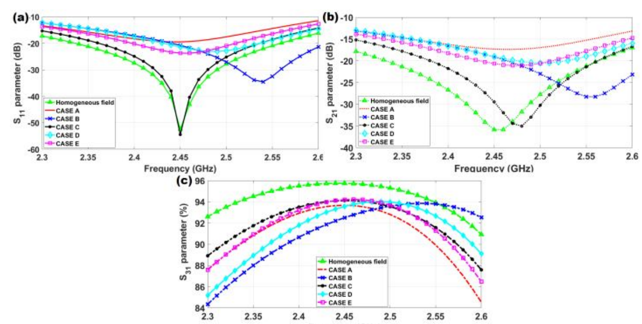

Figure 3: Comparison of S-parameters in homogeneous and non-homogeneous cases.

Conclusion

The present self-consistent model gives more realistic results than that of assumed homogenous field in ferrite with a bandwidth of 100 to 190 MHz which is much border than the industrial WR340 circulators with 50 MHz available in markets. This novel approach can be used for designing different configurations of ferrite circulators while avoiding the error of assuming ideal applied fields.

Acknowledgements

This work was partially supported by the BK21 FOUR program through the NRF funded by the Ministry of Education (NRF-2017H1D8A1032167), Hanyang University (HY-201400000002393) in Korea, and MASTEK, Inc. in Taiwan.

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