Self-Consistent Modeling of Waveguide Circulator Under Realistic Magnetic Field for Industrial Applications

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Abstract: *An RF waveguide circulator is a ferromagnetic passive device with three or four ports, which is used to protect other RF components from excessive signal reflection. The previous studies on the design and development of the circulators deal with achieving broad bandwidth and high transmission efficiency using finite element method (FEM) simulations with a homogenous applied bias field. This work takes a step further and presents a novel self-consistent approach to modeling a ferrite waveguide circulator by solving electromagnetic and magnetostatic equations simultaneously. The comparison between the homogenous and the non-homogenous field models shows the importance of coupling a magnetic circuit to an electromagnetic simulation. The more realistic circulator design presented here still has a broad bandwidth of 180 MHz, insertion loss less than 0.24 dB, reflection, and isolation better than 20 dB operated at the center frequency of 2.45 GHz. It can be used to replace an industrial waveguide circulator, which has only a 50 MHz bandwidth. Hence, by increasing the bandwidth of a circulator, one can reduce the number of units for a dual-frequency magnetrons operating concurrently at 2,430 and 2,480 MHz with a working power of 3 kW each employed in the microwave plasma system.*

Keywords: *Waveguide circulator; self-consistent modeling; magnetron; FEM.*

Introduction

The ferrite waveguide circulator is a radio frequency (RF) device composed of magnetized ferrite material and metallic waveguide components. The non-reciprocal nature of ferrite has been very useful in the application of the microwave region connected with interactions between the spin of 3d electrons and the magnetic field. In general, 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. In both types of circulators, the ferromagnetic oxides of iron employed are not magnetic materials but insulators; hence they have no skin effect of metals, allowing the penetration of high-frequency fields. Therefore, ferrite materials are widely used in microwave devices, isolators, circulators, phase shifters, etc. In addition, the non-reciprocity behavior of the circulator can be used to protect microwave oscillators from the damage due to reflected power from the load such as a plasma processing system. It can also be used to separate the transmitted and received waves in radar or communication systems. The broad bandwidth in these devices with high transmission can be achieved by fine-tuning the materials and geometrical parameters of the ferrite circulator. In general, the design and simulation of a circulator unit were commonly based on electromagnetic simulations, assuming a uniform or homogenous field. In practice, a realistic magnetic circuit would produce a non-uniform field on the ferrite that could affect the bandwidth as well as the transmission efficiency. In this work, the circulator and the magnetic circuit are considered as a whole system in the design and modeling.

3-D Model and Simulation Results

The ferromagnetic material used in the circulator is non-conducting in nature; hence it ensures the total penetration of the electromagnetic field, which is a crucial criterion in waveguide circulator design. In this design, the arrangement of the partial height ferrite in the waveguide circulator supported by an aluminum metal disk attached to the waveguide wall serves an excellent cooling mechanism. This circulator is designed to operate in the S-band region. The circular chamfer design and shape (located at the intersection point of three ports where the ferrite is positioned) along with the metal disc stage play an important role in achieving a wider operating bandwidth from 150 MHz to 210 MHz with its operating frequency centered at 2.45 GHz CCW (Counter Clock Wise). Through optimization techniques and by applying a homogenous bias field of 100 Oe we achieved a 95.74% of transmission at a peak frequency of 2.45 GHz with reflection and isolation parameter of -52.389 and -35.56 dB, respectively, and the -20 dB bandwidth covers a range of 2.34 GHz to 2.55 GHz, nearly 210 MHz bandwidth with a 0.27 dB insertion loss. In the self-consistent model, the magnetic circuit was simulated using FEM with a magnetostatic solver, and the magnetic field obtained was then linked with the electromagnetic solver. The multiphysics coupling completes the self-consistent modeling of the circulator.

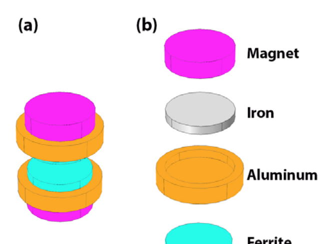

Figure 1: (a) Magnetic circuit and (b) disassembled parts of the magnetic circuit.

The magnetostatic model consists of magnets, iron pieces, aluminum discs, and ferrites. The dimensions of the magnet were optimized based on their magnetic parameters to obtain a magnetic field of approximately 7.1 kA/m across the ferrite diameter such that we obtain a similar magnetic field of 100 Oe or 7.91 kA/m used in the homogenous model. To design a more realistic model, the iron discs are fitted inside the semi-hollow aluminum discs, as shown in Figure 1. The magnets tested were ferrite magnets of FE-48 and Fe-30, and

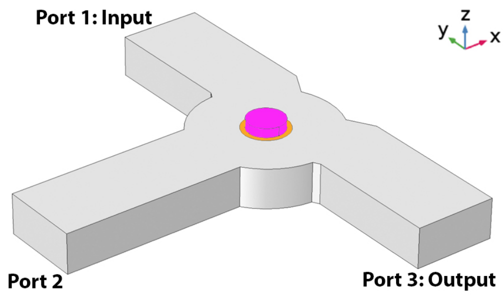

Figure 2: FEM simulation model of the WR340 circulator.

NdFeBr of grade N-35. The ferrite material used here is of grade G-610 that has a magnetic saturation of 680 Oe, linewidth of 40 Oe, and relative permeability of 14.

The non-homogeneous magnetic field obtained from the magnetostatic solver is then passed as an applied bias field in the ferrite tensor matrix for the electromagnetic solver. This introduces the non-uniform magnetic field in ferrite and leads to a self-consistent solution. The bandwidth and transmission obtained by the homogenous and non-homogenous methods are presented in Table I, and their S-parameters are shown in Figures 3 and 4. From the comparison in Table I, the self-consistent model with a non-homogenous applied bias field gives a bandwidth of 180 or 190 MHz, depending on the magnet materials used.

TABLE I: Performance of the WR340 circulator applied with a homogenous field and non-homogenous ones by the magnetic circuits consisting of different magnet materials.

Type		At -20 dB		Transmission (%)	
		Bandwidth (GHz)	Efficiency (%)	Between 2.4 to 2.5 GHz	At 2.45 GHz
Homogenous		2.34 to 2.55 =(210 MHz)	93.91	96.05	95.74
Non-homogenous	FE-30	2.36 to 2.54 =(180 MHz)	94.03	95.38	95.86
	FE-48	2.35 to 2.53 =(180 MHz)	94.28	95.38	95.88
	NdBr (N-35)	2.35 to 2.54 =(190 MHz)	94.11	95.42	95.91

TABLE II: Comparison of magnetic parameters and dimensions of the magnets.

Magnets	Height	B_r	H_c
Fe-48	1 cm	450 mT	342 kA/m
Fe-30	1.5 cm	380 mT	141 kA/m
N-35	0.28 cm	1,230 mT	896 kA/m

The transmission plot in Figure 4 shows that for the same applied field, the transmission remains the same as approximately 94%. The industrial WR340 circulator has a 50 MHz bandwidth, whereas this model gives a 180 MHz bandwidth. Hence, this design would reduce the number of industrial circulator units required for two magnetrons operating concurrently at different frequencies of 2,430 and 2,480 MHz with a working power of 3 kW each.

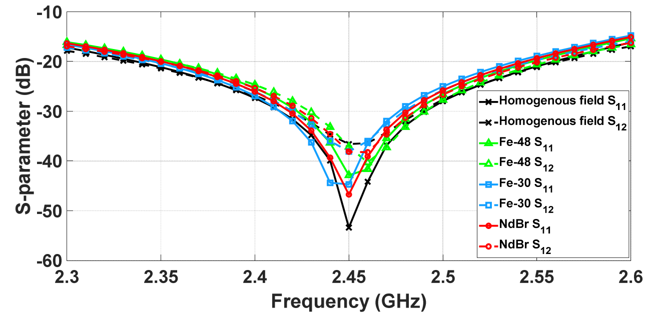

Figure 3: Comparison of S-parameters of the waveguide circulator applied with homogenous and non-homogenous bias fields.

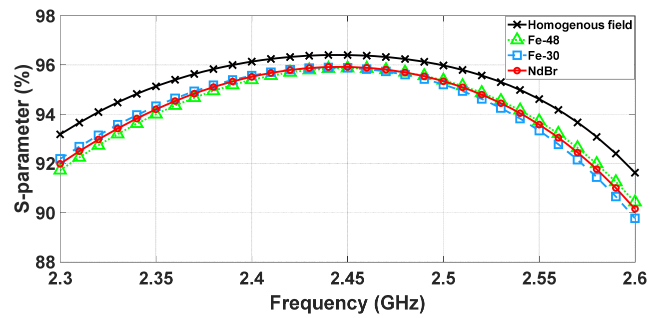

Figure 4: Comparison of transmission of the waveguide circulator applied with homogenous and non-homogenous bias fields.

Conclusion

The self-consistent model solving the magnetostatic circuit and electromagnetic equations gives more realistic results than the former model applied with a homogenous bias field. Under a realistic magnetic circuit bias, a broad bandwidth of 180 MHz, insertion loss less than 0.24 dB, reflection, and isolation better than 20 dB operated at the center frequency of 2.45 GHz can be achieved. It can be used to replace an industrial waveguide circulator, which has only a 50 MHz bandwidth. One can reduce the number of units for a dual-frequency magnetrons operating concurrently at 2,430 and 2,480 MHz with a working power of 3 kW each employed in the microwave plasma system.

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