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A NEW DUAL-BAND HIGH POWER FERRITE CIRCULATOR

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Abstract—The design, simulation and performance enhancement of a new structure for X-band high-power, low-loss, low-bias, triangular-ferrite waveguide circulator are presented. Dual circulation property is obtained by triangular shape of ferrite post. The effects of circulator's structure parameters, such as ferrite parameters and magnetic DC bias, on isolation, insertion loss and return loss of circulator are discussed. The HFSS software is used for simulating the circulators. Final dual band designs with 20 dB return loss, 20 dB isolation and 0.1 dB insertion loss in dual frequency in X-band (8.2 GHz and 10.4 GHz) with only a magnetic bias of 10 Oe are obtained.

1. INTRODUCTION

Circulator is a versatile microwave device which plays an important role in satellite communications and radar applications. There are two different kinds of circulators, E-plane and H-plane, which are based on the two main categories of waveguides. Figures 1(a) and (b) show the three dimensional view and the location of the ferrite in a two dimensional view of E- and H-plane circulators. Each of them has advantages which stems from the properties of the waveguide used as the guiding structure or the location of the ferrite in the circulator structure. In general, the power handeling of the E-plane circulator is higher than the H-plane. This is due to the fact that the ferrite is located at the point where the electric field is minimum in the waveguide. In addition, RF losses caused by the dielectric properties of the ferrite will be smaller, thereby reducing the heating effects.

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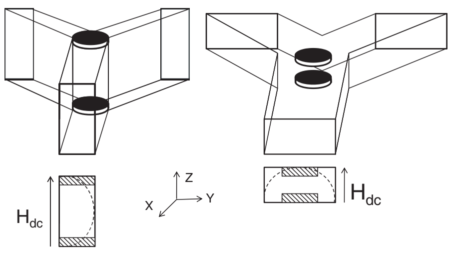

Figure 1. Geometries of E-plane and H-plane junctions of waveguide circulators. Dotted line = Electric field intensity.

Another problem that reduces the handling of high-power application is that ferrite is a brittle material. Increasing the amplitude of one of E or H fields to extremely high value in the ferrite region may tends to ferrite crashing. An optimum way to keep it safe against any damage is to place it in a dielectric substrate.

There have been several theoretical attempts to analyze and design different E-plane waveguide circulators [7, 9]. These analysis has led to different physical implementations of E-plane circulators [1–4]. But, as far as we know there has not been any theocratical or experimental attempts to design dual band circulator in the literature. In this paper, a design procedure for high-power, dual-band or Left-Handed Right-Handed (LH-RH) dual-band circulator is presented. The Ansoft HFSS software is employed to optimize the response of circulator.The first part includes a brief theory of the dual band ferrite circulator and different techniques which can be used to increase the bandwidth and decrease the insertion loss. The second part includes the design process and optimization results.

2. THEORY OF THE DUAL BAND CIRCULATOR

In the first Section 2.1 general description of a dual band circulator in terms of its ideal scattering parameters is presented. A practical example which shows the application of the dual band circulator in a transmitter system is also included in this section. In the next two sections different techniques which can be used to achieve wider bandwidth and lower reflection loss are discussed. The last Section 2.4 talks about the modal distribution of the ferrite inside the circulator.

2.1. Dual Band Circulator

In general, circulators are three port networks. Hence, the associated scattering parameters matrix is a 3 by 3 matrix. There are two possible representation for a lossless circulator which is defined as $\mathbf{S_{LH}}$ and $\mathbf{S_{RH}}$ with S parameter matrices,

$$\mathbf{S_{LH}} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \qquad \mathbf{S_{RH}} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

In a "left handed circulator" (LHC) which is defined by S_{LH} the signal circles counterclockwise and in the "right hand circulator" (RH) which is defined by S_{RH} the signal circle in the clockwise direction. Any single band circulator adopts one of these arrangements.

In a dual band circulator there are two possible demonstration. A regular dual band circulator has right hand or left hand circulation in two different frequency bands. But, another possibility is a "LH-RH dual band circulator" which has right hand circulation in one frequency band and left hand circulation in an other one. Left hand-right hand (LH-RH) circulators can be used as power combiner in dual-band or multi-band transmitters [13] or in Radar applications. As illustrated in Figure 2(a), a LH-RH dual-band circulator can be used to mix two high power transmitters and send the signals with one broadband antenna. At the same time, the system provides proper isolation between two transmitters for multiplexing different channels. Another application (Figure 2(b)) is implementing the power sections of a dual-band radar by means of two simple dual-band circulators (or two broadband circulators) and one LH-RH dual-band circulator.

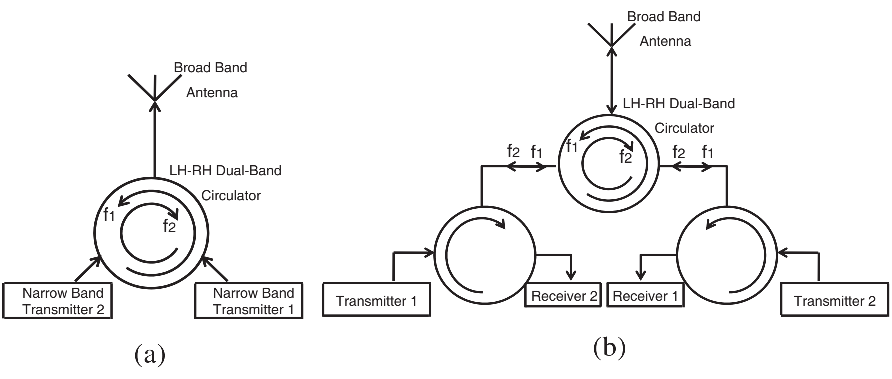

Figure 2. Schematics of two applications for LH-RH dual-band E-plane circulator.

2.2. Bandwidth

One important property of a circulator is its bandwidth which is different for E- and H-plane structures. Although E-plane circulators have the capability of high power handeling, generally their bandwidth is narrower compared to the H-plane structures. Hence, in general there is a tradeoff between bandwidth and high-power handling properties. The physical structure of the E- and H-plane waveguides dictates this trade-off. In most of the applications the high power capability is superior to the bandwidth, hence, most of the circulators are E-plane. But, some specific alteration in the ferrite structure may lead to increasing the bandwidth in the E-plane structure. For example, increasing the height of the ferrite post increases the bandwidth. But, as the result of increasing the length of the ferrite, concentration of the peak of TE_{10} mode in the ferrite region increases which decreases the high-power capability of the circulator. Another way to to broaden the bandwidth is done by improving the impedance match of the ferrite junction. A well known technique is placing a stack of thin dielectric disks of diminishing dielectric constant on top of each ferrite disk [14]. Adding a single dielectric would also increase the bandwidth but it has a lower impact. Here, we have placed two short lengths of the ferrite on both sides of the E-plane waveguide to increase the high power capability of the circulator. Also, the space between the two pieces of ferrite is filled with a dielectric to increase the bandwidth (Figure 3).

2.3. Reflection Loss

The shape of the ferrite post plays an important role in matching of the junction to the waveguide structure. In general tapering the cross section of the ferrite in the direction of the incident wave decreases the reflection loss. The triangular intersection is used in several cases [8, 15] to decrease the reflection loss. As illustrated in Figure 4, implementing the triangular ferrite can be done in two different geometries. Based on the performed simulations structure (a) has a better insertion loss than (b). This is due to the fact that the propagating wave in Figure 4(a) hits the tapered side of the ferrite post while in Figure 4(b) it faces with the flat surface of ferrite post, so the reflection in Figure 4(b) is considerably larger than the reflection of tapered ferrite in the geometry of Figure 4(a).

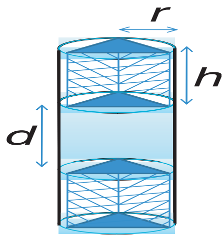

Figure 3. Physical geometry of the triangular ferrite posts and the dielectric filling around them.

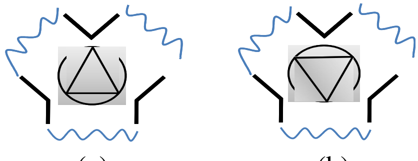

Figure 4. Geometries of two kinds of ferrite placement in the waveguide junction.

2.4. Modal Description of the Ferrite in E-plane Circulator

To simplify the analysis of the structure we have assumed that the ferrite post and the dielectric filling have similar dielectric constant. Hence, we can assume that the combination of the ferrite and the dielectric filling form a cylindrical dielectric resonator. The theory of fundamental cylindrical dielectric resonator mode presented in [5, 6]. Based on this approximation the lowest order mode of the ferrite resonator is the TM_{111} mode which is the dominant cylindrical dielectric resonator. In the E-plane circulator the half height ferrite is placed on the side wall of a waveguide as shown in Figure 1. The normal mode components, E_z and H_y of the TE_{10} waveguide can couple to the similar field components of the ferrite resonator. The application of a dc magnetic field in the Z direction will reorient the standing wave of the resonator. With a proper reorientation a three-port circulator will be obtained. The reorientation of the standing wave is caused by the splitting of the TM_{111} mode into the TM_{111}^{+} and TM_{111}^{-} modes by the tensor permeability of the ferrite resonator. These modes correspond to right-handed and left-handed circular polarization respectively. By controlling the degree of this split, it is possible to adjust the resonant frequency of circulator for gaining a nonreciprocal response.

Assuming the dielectric resonator fills the full height of the waveguide junction, the approximate center frequency of the split mode in free space is [5, 10–12],

$$\frac{2\pi r}{\lambda_0}\sqrt{\epsilon\mu_{\mathit{eff}} - \frac{\lambda_0}{2L}} = 1.84 \tag{1}$$

where λ_0 is the free space wavelength, r is the radius of the cavity, ϵ is the relative permittivity, μ_{eff} is the relative effective permeability and is the full height of the cavity which is defined as,

$$\mu_{eff} = \frac{\gamma^2(H_0 + 4\pi M_0)^2 - \omega^2}{\gamma^2 H_0(H_0 + 4\pi M_0)^2 - \omega^2} \tag{2}$$

where, γ is the gyromagnetic ratio, ω is the angular frequency, H_0 is the internal dc magnetic field and $4\pi M_0$ is the saturation magnetization.

3. DESIGN AND SIMULATION RESULTS

The design process of the dual band circulator includes two parts. In the first part, we will design a regular three port E-plane triangular ferrite circulator which is illustrated in Figure 1. The circulator structure consists of a Y-junction waveguide with a post mounted in the center of the junction. The post is a composed of two pieces of ferrite on the top and bottom. The ferrite pieces are surrounded by a cylindrical dielectric. The gap between two ferrite pieces is also filled with the same dielectric by length d. A DC magnetic bias field is applied to the waveguide perpendicular to the plane of Y-junction. The design procedure is general, but since simulations are in X-band, the waveguides are assumed to be WR-90.

To obtain the resonant frequency of the structure for TM_{111} mode we set the internal magnetic bias to zero. Equation (1) provides the relation between resonant frequency and radius of the cavity. The radius of the cavity is plotted with respect to frequency in Figure 5 in the range between 8 to 12 GHz. This curve is used in the design procedure, a circulation frequency is selected and by means of Figure 5 the corresponding radius of resonator can be obtained. Applying a DC internal magnetic field to ferrite, the TM_{111} mode splits and the resonant frequency of the structure may change from the one obtained from Figure 5. This only provides us with a initial guess which has to be optimized. After some tuning using the HFSS software a single band E-plane circulator is achieved. Its S-parameters are shown in Figure 6. It is circulator with 15 dB return loss, 17 dB isolation and 0.1 dB insertion loss with 8% bandwidth frequency. The parameters of the ferrite are based on the commercial ferrite from Trans Tech and Temex.

The next step is designing the dual band circulator. The single band circulator which is designed previously is used as a initial step in the design process. In the next step we have tried to achieve the dual band property by changing the parameters of the structure. There are two different types of parameters involved in the ferrite circulator, ferrite material parameters and structural parameters. To investigate the effect of each of these parameters on circulator characteristics we

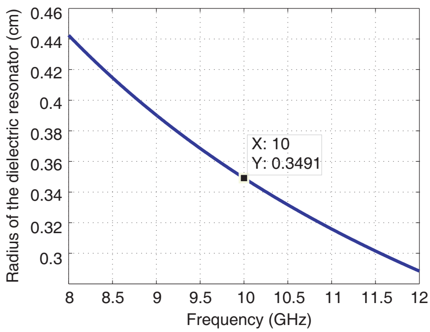

Figure 5. Radius of the dielectric resonator at different frequencies.

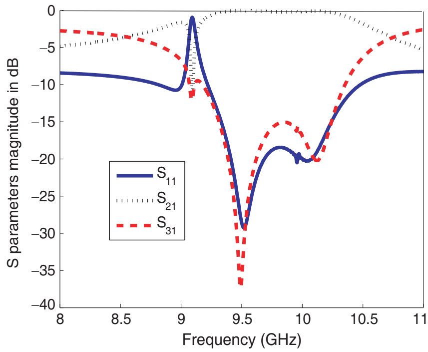

Figure 6. S-parameters of single-band E-plane circulator. Dimensions: $d = 3.5\,\mathrm{mm}$, $r = 3.38\,\mathrm{mm}$, ferrite: TTVG-930 and internal bias: $H_0 = 10\,\mathrm{Oe}$.

have done two sets of simulations based on the initial design. In the first set we have studied the effect of the ferrite material parameters on the circulator characteristics. The ferrite material parameters are M_0, H_0, ΔH, and ϵ, where, M_0 is the saturation magnetization, H_0 is the magnetic dc bias, ΔH is the line-width, and ϵ is the dielectric constant of the ferrite. Results of these simulations are shown in Table 1. The starting point of each parameter is the ones obtained in the design procedure of the single band circulator. The table shows the variations of circulator performance parameters (Δf, I, IL, RL, f_0) as each of the physical parameters (M_0, H_0, ΔH, ϵ) change. The variation of the physical parameters is limited to the range which the performance parameters change monotonically (250% for M_0, 500% for H_0, 250% for ΔH, and 15% for ϵ). In Table 1, M means a relative maximum and m means a relative minimum. Among these parameters, M_0 has the most effect on the circulator characteristics and the double band property is achieved by just tuning its value. The other material parameters can be used for fine tuning the double band circulator.

In another set of simulations we have studied the effect of the ferrite structural parameters on the performance of the circulator. These parameters are the length of the ferrite (h), the deviation of the ferrite from a complete triangular shape (S), and the radius of the dielectric surrounding the ferrite. The deviation from the start point is 45% in h, 33% in S, and 5% in r. Figure 7 shows the three different shapes of the ferrites which is specified by parameter S in the simulation results in Table 2. A simple dual band and a LH-RH

Table 1. Ferrite material parameters optimization (Δf (dual band frequency deviation), I (Isolation), IL (Insertion Loss), RL (Return Loss), f_0 (Center Frequency)), (M means a relative maximum and m means a relative minimum).

	$M_0\downarrow$	$M_0\uparrow$	$H_0\downarrow$	$H_0\uparrow$	$\Delta H\downarrow$	$\Delta H\uparrow$	$\epsilon\downarrow$	$\epsilon\uparrow$
Δf	−	+	−	+	cte	cte	−	−
I	M	M	+	−	+	−	−	M
IL	m	m	−	+	−	+	+	m
RL	M	M	+	−	+	−	−	M
f_0	−	+	−	+	cte	cte	+	−

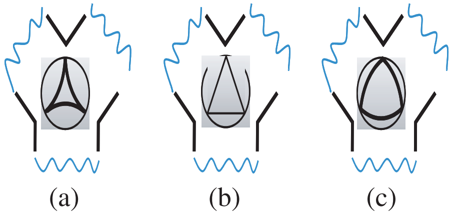

Figure 7. Shape optimization of the triangular ferrite.

Table 2. Ferrite shape optimization (Δf (dual band frequency deviation), I (Isolation), IL (Insertion Loss), RL (Return Loss), f_0 (Center Frequency)) (M means a relative maximum and m means a relative minimum).

	$h\downarrow$	$h\uparrow$	$S\downarrow$	$S\uparrow$	$r\downarrow$	$r\uparrow$
Δf	+	−	+	−	−	cte
I	−	+	−	M	−	−
IL	+	−	+	m	+	+
RL	−	+	−	M	−	−
f_0	+	−	−	−	+	−

dual band ferrite circulator are achieved based on these optimization results. The S-parameters of the simple dual- band E-plane circulator are shown in Figure 8. It has 20 dB return loss, 20 dB isolation and 0.1 dB insertion loss in 8.2 GHz and 10.35 GHz. Scattering parameters of the LH-RH dual-band E-plane circulator are shown in Figure 9 which has 20 dB return loss, 20 dB isolation and 0.1 dB insertion loss in 9.95 GHz and 11.9 GHz. In all three final designs the ferrite parameters matches one of the commercial ferrites which are listed in Table 3.

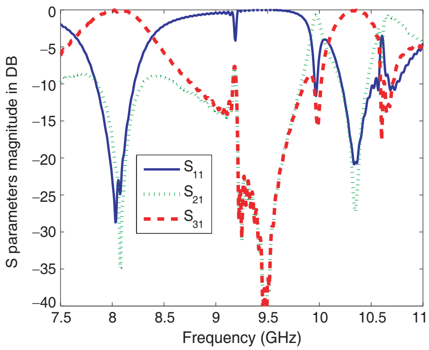

Figure 8. S-parameters of dual-band E-plane circulator. Dimensions: $d = 3.5$ mm, $r = 3.38$ mm, ferrite: TTVG-930 and internal bias: $H_0 = 10$ Oe.

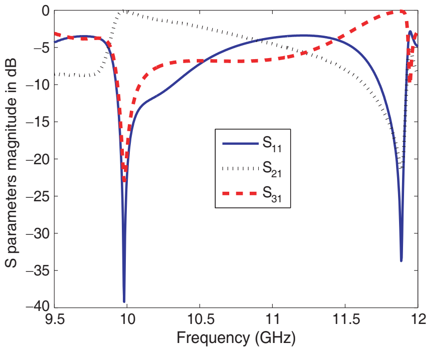

Figure 9. S-parameters of dual-band E-plane circulator. Dimensions: $d = 3.5$ mm, $r = 4.55$ mm, ferrite: Y331 and internal bias: $H_0 = 10$ Oe.

Table 3. Commercial ferrite parameters used in the final designs.

Ferrite	M_0	$\tan\delta$	ϵ	ΔH	g_{eff}
TTVG-930	930	0.0002	14	10	2
Y331	615	0.0002	14.5	22	2.01
TTVG-1850	1850	0.0002	14.8	10	2

4. SUMMARY AND CONCLUSION

A new structure for high power E-plane X-band circulator is presented. Simulations demonstrate that this structure can have two types of dual-band response, simple dual-band and LH-RH dual-band. Design procedure for both dual-band structures is presented.

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