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Magnetic Parameters for Ultra-high Frequency (UHF) Ferrite Circulator Design

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We designed an ultra-high frequency (UHF: 300 MHz to 3 GHz) ferrite circulator to investigate magnetic parameters, which are suitable for a self-biased GHz circulator design. The size of the ferrite disk was 1.58 mm in thickness and 13.5 mm in diameter. The saturation magnetization ($4\pi M_s$) of 3900 Gauss, internal magnetic field (H_{in}) of 1 kOe, and ferromagnetic linewidth (ΔH) of 354 Oe were used in circulator performance simulation. The simulation results show the isolation of 36.4 dB and insertion loss of 2.76 dB at 2.6 GHz and were compared to measured results. A Ni-Zn ferrite circulator was fabricated based on the above design parameters. An out-of-plane DC magnetic field (H_0) of 4.8 kOe was applied to the fabricated circulator to measure isolation, insertion loss, and bandwidth. Experimental magnetic parameters for the ferrite were H_{in} of about 1.33 kOe and $4\pi M_s$ of 3935 Gauss. The isolation 43.9 dB and insertion loss of 5.6 dB measured at 2.5 GHz are in close agreement with the simulated results of the designed ferrite circulator. Based on the simulated and experimental results, we demonstrate that the following magnetic parameters are suitable for 2 GHz self-biased circulator design: $4\pi M_r$ of 3900 Gauss, H_a of 4.5 kOe, H_c greater than 3.4 kOe, and ΔH of 50 Oe.

Keywords : ferrite circulator, magnetic parameters, magnetization, internal field, ultra-high frequency (UHF)

1. Introduction

Circulators [1-3] are used to enable simultaneous transmission and reception of radio frequency (RF) signals at the RF front-end transceiver. Accordingly, Y-junction stripline and lumped element ultra-high frequency (UHF: 300 MHz-3 GHz) ferrite circulators were developed [4, 5]. The stripline junction circulator, fabricated on a garnet disk with the saturation magnetization ($4\pi M_s$) of 750 Gauss, showed the isolation of 40 dB and insertion loss of 1 dB at 2.7 GHz. On the other hand, a spinel ferrite disk with $4\pi M_s$ of 1850 Gauss and coercivity of 0.5 Oe was used for the lumped element circulator. This circulator exhibited isolation better than 20 dB, insertion loss of 0.7 dB, and bandwidth of about 160 MHz (240-400 MHz). Both the garnet and ferrite are magnetically soft, thereby requiring bias magnetic field, i.e. permanent magnets, to align magnetic spins out of the plane. This leads to a bulky circulator; therefore, self-biased circulators need to be developed.

In an effort to address the above issue, a self-biased UHF circulator was designed with an yttrium iron garnet (YIG) nanowires embedded in a barium-strontium titanate and simulated for its operation performance [6] at 1 GHz. The $4\pi M_s$ of 398 Gauss and a large out-of-plane shape anisotropy were assumed for the YIG, but the anisotropy value was not reported. Furthermore, the YIG nanowires were assumed to be fully magnetized in the out-of-plane direction. The simulation results show an isolation of 40 dB, insertion loss of 0.16 dB at 1 GHz, and bandwidth of 50 MHz. These results are not yet verified by experiments. There is no report on experimental UHF self-biased circulators. This is because no out-of-plane anisotropy thick magnetic films with high resistivity are available yet for UHF self-biased circulators. Magnetic material specifications suitable for UHF self-biased circulators will help design and fabricate the UHF circulators.

In this paper, we designed a Y-junction UHF ferrite circulator to find design parameters, suitable for high-isolation and self-bias operation of a Y-junction circulator, and experimentally confirmed the parameters.

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2. Design of Ferrite Circulator

Non-reciprocal ferrite circulators arise from the asymmetrical permeability tensor in Eqs. (1) and (2) [7]

$$[\mu] = \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad (1)$$

$$\mu = 1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}, \quad \kappa = \frac{\omega \omega_m}{\omega_0^2 - \omega^2}, \qquad (2)$$

where μ is the diagonal term, κ is the off-diagonal term, ω_m is the magnetization frequency ($\gamma 4\pi M_s$), and ω_0 is the gyromagnetic frequency ($\gamma H_{\rm in}$). Both μ and κ elements result in two different modes ($\mu_+ = \mu + \kappa$ and $\mu_- = \mu - \kappa$) of circularly polarized waves (i.e., left- and right-hand circular polarizations) in the magnetized ferrite disk. The interaction of a circularly polarized wave with the magnetic spin precession in the same sense experiences a large attenuation. On the other hand, a small attenuation occurs for a circularly polarized wave rotating in the opposite sense of the spin precession [8]. Thus, non-reciprocal wave propagation of a ferrite circulator can be realized. Both μ and κ depend on the ferrite magnetic parameters given in Eq. (2). The parameters include saturation magnetization ($4\pi M_s$) and internal magnetic field ($H_{\rm in}$), where the $H_{\rm in}$ is the sum of the applied DC magnetic field (H_0), anisotropy field (H_a), and demagnetization field (H_d) as given by Eq. (3)

$$H_{in} = H_0 + H_a - H_d. \qquad (3)$$

Therefore, the $4\pi M_s$, $H_{\rm in}$, and ferrite disk radius (R) are key design parameters to determine the operating frequency and electrical characteristics of a ferrite circulator.

We designed an UHF Y-junction ferrite circulator operating in the frequency band of 2 to 3 GHz. The R of the ferrite disk resonator was calculated by Eq. (4) to meet the desired frequency band [9]

$$R = \frac{1.84}{k} = \frac{1.84}{\omega\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_{eff}}} = \frac{1.84 \times c_0}{2\pi f \sqrt{\varepsilon_{r,ferrite} \mu_{eff,ferrite}}}, \qquad (4)$$

where k is the wavenumber, ω is the circulator operation angular frequency ($= 2\pi f$), c_0 is the velocity of light in vacuum, $\varepsilon_{r,ferrite}$ is the dielectric constant, and $\mu_{eff,ferrite}$ is the effective permeability of the ferrite disk. Eq. (5) [10] was used to calculate the $\mu_{eff,ferrite}$,

$$\mu_{eff,ferrite} = \frac{\mu^2 - \kappa^2}{\mu}. \qquad (5)$$

After inserting $4\pi M_s$ of 3900 Gauss and H_{in} of 1380 Oe in Eqs. (2) and (5), the $\mu_{eff,ferrite}$ is obtained to be 4.10. These $4\pi M_s$ and H_{in} values were chosen to meet operation frequency of 2 to 3 GHz. Then, the calculated R becomes 6.75 mm when $\varepsilon_{r,ferrite}$, $\mu_{eff,ferrite}$, and f are 7.8, 4.1, and 2.3 GHz, respectively.

Next, 50 Ω microstrip lines between the ferrite resonator and 50 Ω input ports were designed. We used equation (6) to calculate a width (w) of the microstrip line [11].

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff,dielectric}}} \times \frac{1}{\left(\frac{w}{h} + 1.393 + 0.677\ln\left(\frac{w}{h} + 1.444\right)\right)}, \qquad (6)$$

$$\varepsilon_{eff,dielectric} = \frac{\varepsilon_{r,dielectric} + 1}{2} + \frac{\varepsilon_{r,dielectric} - 1}{2}\left(1/\sqrt{1 + \frac{12h}{w}}\right),$$

where Z_0 is the input port impedance, $\varepsilon_{r,dielectric}$ is the dielectric constant, and h is the height of the dielectric substrate. In this calculation, $\varepsilon_{r,FR4}$ of 4.6 and h of 1.50 mm for dielectric FR4 substrate (tan $\delta_{\varepsilon,FR4}$ of 0.02), and Z_0 of 50 Ω were used. The calculated w is 2.77 mm. However, performance optimization with the 3-D EM simulation (using ANSYS HFSS ver. 11) showed that w of 2.3 mm further improved impedance matching. Therefore, we used the w of 2.3 mm in our ferrite circulator design.

Based on the above calculated R and w, a Y-junction ferrite circulator was designed as shown in Fig. 1. Then, we performed 3-D EM simulation of the designed circulator to characterize isolation (S_{12}) and insertion loss (S_{21}), using our experimental FMR linewidth (ΔH) of 354 Oe and tan $\delta_{\varepsilon,ferrite}$ of 0.04 at 2.5 GHz for Ni-Zn ferrite disk. The internal field $H_{\rm in}$ was considered to be in the out-of-plane direction and varied from 0 to 2.0 kOe.

Figure 2 shows the simulated isolation and insertion loss of the designed ferrite circulator. The isolation is better than 20 dB with H_{in} in the range of 0.8 to 1.38 kOe at 3900 Gauss of $4\pi M_s$, and the circulator resonant fre-

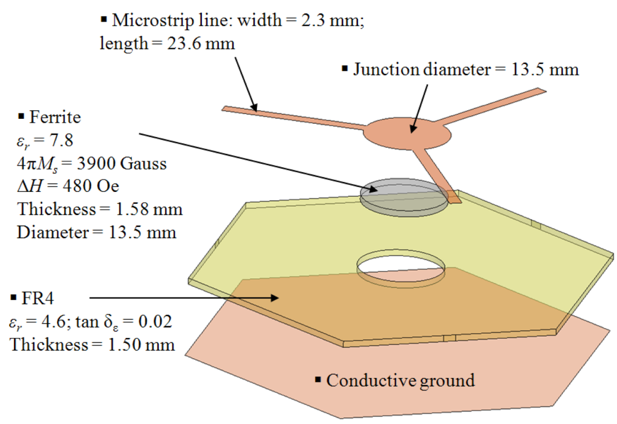

Fig. 1. (Color online) Designed Y-junction ferrite circulator for performance simulation.

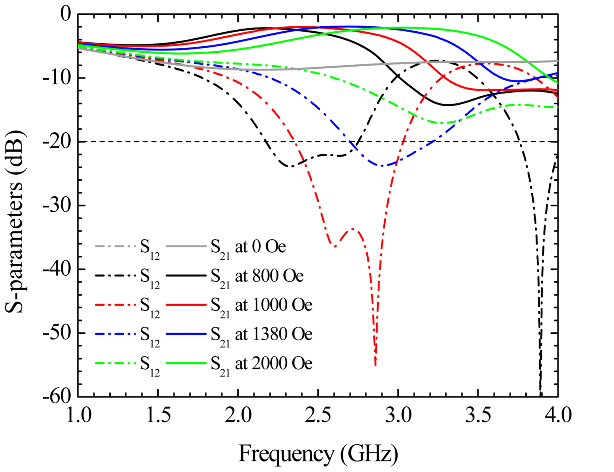

Fig. 2. (Color online) Simulated isolation (S_{12}) and insertion loss (S_{21}) of the designed Y-junction ferrite circulator with various internal fields (H_{in}) at $4\pi M_s$ of 3900 Gauss.

quency shifts toward higher frequency with the H_{in} due to a decrease in $\mu_{eff,ferrite}$. The isolation reaches 36.4 dB at 2.6 GHz, and the 20 dB-isolation bandwidth is 0.68 GHz at H_{in} of 1 kOe. The average insertion loss over the 20 dB-isolation bandwidth is 2.76 dB. It is found that the circulator exhibits reciprocal characteristic ($S_{21} = S_{12}$) without H_{in}. The H_{in}, therefore, plays a key role in realizing the non-reciprocal circulator. Table 1 summarizes the minimum insertion loss, maximum isolation, and bandwidth of the circulator with $4\pi M_s$ of 3900 Gauss at various values of H_{in}.

3. Fabrication of Ferrite Circulator and Measurement

To verify simulated magnetic parameters in section 2, we fabricated a $Ni_{0.65}Zn_{0.35}Fe_2O_4$ (Ni-Zn) ferrite circulator based on the designed circulator in Fig. 1. A photo-image of the fabricated circulator is shown in Fig. 3. In this study, the Ni-Zn ferrite was used on purpose because the H_{in} of the ferrite is changed with an applied DC magnetic field according to Eq. (3). A Ni-Zn ferrite disk, with a diameter of 13.5 mm and thickness of 1.58 mm, was prepared by pressing and sintering a ferrite green disk at 1200 °C for 5 hours. Symmetrical microstrip lines (width: 2.3 mm, length: 23.6 mm, copper thickness: 0.045 mm) were fabricated on the dielectric FR4 board ($\varepsilon_{r,FR4}$: 4.6, tan $\delta_{\varepsilon,FR4}$: 0.02, thickness: 1.50 mm), and 50 Ω SMA connectors were attached to the lines. Then, the ferrite disk was embedded into the center of the FR4 board with an epoxy adhesive. Circulator performance was then characterized in the frequency range of 1 to 4 GHz. For scattering parameter measurements, the port 1 and 2 of the circulator were connected to the port 1 and 2 of a vector network analyzer, respectively. In order to eliminate undesired signal from the port 3 of the circulator, a 50 Ω terminator was connected to the port. We used an electromagnet to apply DC bias magnetic field in out-of-plane direction to ferrite disk, and an impedance/material analyzer, a ferromagnetic resonance (FMR) system, and vibrating sample magnetometer (MicroSense EV9) to mea-

Table 1. Simulated characteristics of the designed Y-junction ferrite circulator with various internal fields (H_{in}).

H_{in} (kOe)	0	0.8	1.0	1.38	2.0
Minimum insertion loss (dB)	8.7	2.2	2.0	1.9	2.1
Maximum isolation (dB)	8.7	22.2	55.0	23.7	17.0
Bandwidth at 20 dB isolation (GHz)	N/A	0.57	0.68	0.51	N/A

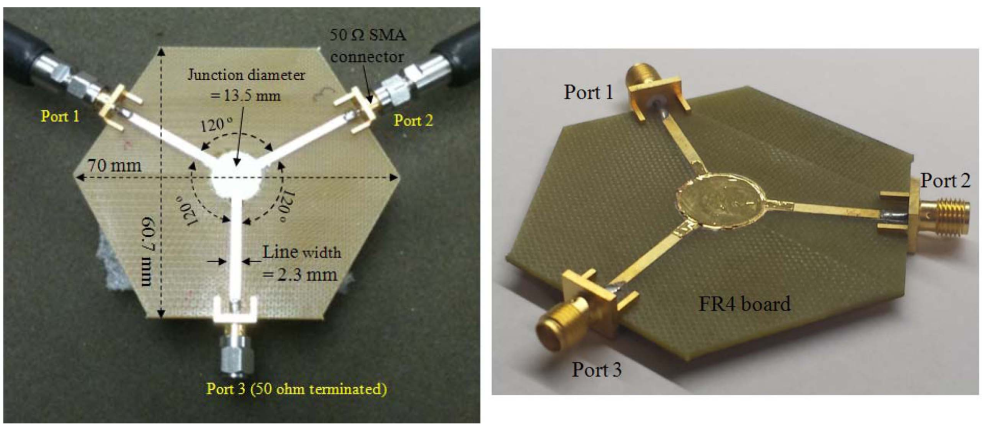

Fig. 3. (Color online) Fabricated Y-junction Ni-Zn ferrite circulator.

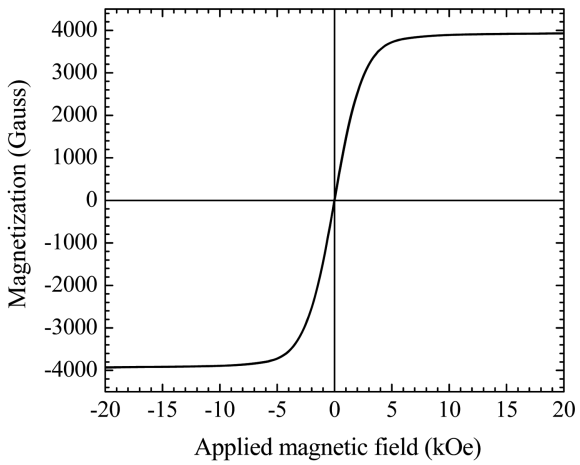

Fig. 4. Measured magnetic hysteresis loop of the Ni-Zn ferrite disk.

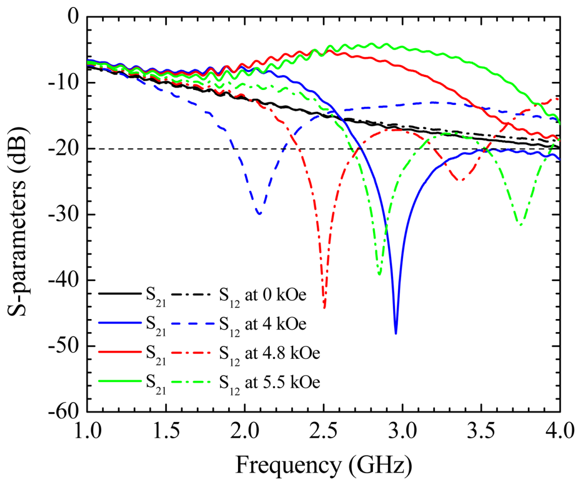

Fig. 5. (Color online) Measured isolation (S_{12}) and insertion loss (S_{21}) of the fabricated Y-junction ferrite circulator with various DC biased magnetic fields (H_0).

sure dynamic and static magnetic properties of the Ni-Zn ferrite disk.

The measured $4\pi M_s$ and coercivity (H_c) are 3935 Gauss and 8.3 Oe, respectively, as shown in Fig. 4. It is noted that the ferrite starts to saturate at 4.8 kOe. Permittivity, $\varepsilon_{r,ferrite}$, and FMR linewidth, ΔH, were measured to be 7.8 (tan $\delta_{\varepsilon,ferrite}$ = 0.04) and 354 Oe at 2.5 GHz (FMR spectrum is not shown here.).

Figure 5 shows isolation and insertion loss measured with various DC biased fields (H_0). The isolation is better than 30 dB at H_0 higher than 4 kOe, and the maximum isolation of 43.9 dB is obtained at 4.8 kOe of H_0 and 2.5 GHz. This H_0 corresponds to H_{in} of about 1.33 kOe because of $H_{in} = H_0 + H_a - H_d$ = 4.8 kOe – (0.88 × 3935 Gauss), where H_a is negligible for the Ni-Zn ferrite. The demagnetization factor (N_z = 0.88) of the ferrite disk was calculated at the aspect ratio (m = ferrite radius/thickness) of 4.3 using Eq. (7) [12]

$$N_z = 1 + m - \sqrt{1+m^2}\,. \qquad (7)$$

The 20 dB-isolation bandwidth of the fabricated circulator is 0.38 GHz at 4.8 kOe of H_0. This is in close agreement with simulated isolation and bandwidth. Furthermore, the minimum insertion loss is in the range of 4 to 8 dB as the H_0 changes from 4 to 5.5 kOe. These insertion losses are higher than the simulated results given in Table 1. This is attributed to additional losses from the transmission line, the gap between the ferrite disk and FR4 board, and partially saturated ferrite disk at low H_0. It is evident that the circulator shows the reciprocal behavior ($S_{21} = S_{12}$) when no bias field is applied to the ferrite disk. The measured performance parameters are summarized in Table 2. It is found that the experimental and simulation results are in close agreement. These results confirm that the designed ferrite magnetic parameters, $4\pi M_s$ of 3900 Gauss and H_{in} of 1 kOe, are suitable for the design of a high-isolation 2 GHz circulator.

However, to realize self-bias operation of a ferrite circulator, the ferrite corevicity (H_c) must be greater than demagnetization field given in Eq. (8) [13],

$$H_c > N_z 4\pi M_r\,. \qquad (8)$$

This is because the H_c mitigates the demagnetizing effect, therefore, retaining a large remnant magnetization. Furthermore, a moderately large H_a of ferrite is necessary to keep an appropriate H_{in} without an external DC bias field. Therefore, $4\pi M_r$ of about 3900 Gauss, H_c greater than 3.4 kOe ($\geq N_z 4\pi M_r$ = 0.88 × 3900 Gauss), and H_a of about 4.5 kOe ($H_a = H_{in} + H_d - H_0$ = 1 kOe + (0.88 × 3935 Gauss) – 0 Oe) are desired to realize self-bias operation of a ferrite circulator. The magnetic and simulated performance para-

Table 2. Measured performance parameters of the biased Y-junction Ni-Zn ferrite circulator.

DC magnetic field, H_0 (kOe)	0	4	4.8	5.5
Internal field (H_{in}) (kOe)	0	0.53	1.33	2.03
Minimum insertion loss (dB)	14.9	8.1	5.6	4.7
Maximum isolation (dB)	14.9	29.9	43.9	39.0
Bandwidth at 20 dB isolation (GHz)	N/A	0.33	0.38	0.43

Table 3. Magnetic and simulated performance parameters of a designed self-biased ferrite circulator.

Desired magnetic parameters	
Remanent magnetization ($4\pi M_r$)	3900 Gauss
Anisotropy field (H_a)	4.5 kOe
Coercivity (H_c)	$\geq N_z 4\pi M_r$ = 3.4 kOe
FMR linewidth (ΔH)	50 Oe
Simulated performance parameters	
Isolation	30 dB at 2.59 GHz
Insertion loss	0.78 dB
Bandwidth at 20 dB isolation	0.58 GHz (2.38-2.96 GHz)

meters of a designed self-biased ferrite circulator are summarized in Table 3. The simulated isolation, insertion loss, and bandwidth are 30 dB at 2.59 GHz, 0.78 dB, and 0.58 GHz, respectively. It is noted that insertion loss of the ferrite circulator decreases by the loss factor ΔH. These parameters give guidelines to the development of high-isolation self-biased circulators in the UHF band. Searching for ferrites finds the following M-type hexaferrite ($SrFe_{12}O_{19}$) that meets the desired magnetic parameters. This hexaferrite shows 18 kOe of theoretical H_a and 4735 Gauss of $4\pi M_s$ [14], which are too large for UHF self-biased circulator applications. However, magnetocrystalline anisotropy and magnetization of the M-type hexaferrite can be tailored by substituting non-magnetic cations for five Fe^{3+} different crystallographic sites (2*a*, 12*k*, 4f_1, 4f_2, and 2*b*) of M-type hexaferrite to make it suitable for UHF self-biased ferrite circulators. Therefore, substituted M-type hexaferrite is a potential candidate for UHF self-biased ferrite circulator.

4. Conclusion

We designed a Y-junction ferrite circulator with a 1.58 mm-thick, 13.5 mm-diameter ferrite disk to investigate magnetic parameters, which are suitable for the UHF self-biased circulator design. Saturation magnetization ($4\pi M_s$) of 3900 Gauss, internal magnetic field (H_{in}) of 1 kOe, and ferromagnetic linewidth (ΔH) of 354 Oe were assumed for the ferrite. Our circulator performance simulation shows the isolation of 36.4 dB and insertion loss of 2.76 dB at 2.6 GHz.

In order to confirm the results from the designed circulator, we fabricated a Ni-Zn spinel ferrite circulator based on the above design parameters and applied a DC magnetic field (H_0) of 4.8 kOe. Experimental magnetic parameters for the ferrite were H_{in} of about 1.33 kOe and $4\pi M_s$ of 3935 Gauss. The isolation 43.9 dB and insertion loss of 5.6 dB measured at 2.5 GHz are in close agreement with the simulated results of the designed ferrite circulator.

Based on the designed ferrite geometry and parameters, and experimental results, it is concluded that the following magnetic parameters are suitable for 2 GHz self-biased circulator design: $4\pi M_r$ of 3900 Gauss, H_a of 4.5 kOe, H_c greater than 3.4 kOe, and ΔH of 50 Oe.

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