SAN JOSE STATE UNIVERSITY

College of Engineering

Department of Electrical Engineering

Final Project EE172 course

Report

Stripline Circulator

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May 28, 2011

ABSTRACT

The operation of symmetrical circulator is described in term of the counter rotating normal mode of the ferrite. The rotating modes are applied by magnetic field form a stationary pattern which can be rotated in space to isolate one of the ports of the circulator. A field theory of the strip-line Y- junction circulator operating with n=1 will be presented in this report. This report includes equation designs, material of ferrite, dimensions and result of simulation by High Frequency Simulation Structure (HFSS).

INTRODUCTION

The three port circulator is a unique nonreciprocal symmetrical junction having one typical input port, one output port, and one decoupled port. The purpose of junction circulator is energy conservation. It means that the only matched three port junction corresponds to the definition of the circulator. A wave incident in such a junction at port 1 is emergent at port 2, one incident at port 2 is emergent at port 3, and so on is a cyclic manner. The purpose of introduction in this report is to provide the phenomenological description of the operation of this device.

The geometry of the stripline circulator geometry is showed in Fig 1. It consists of two ferrite planar disk resonators separated by a disk center conductor symmetrically coupled by three transmission lines.

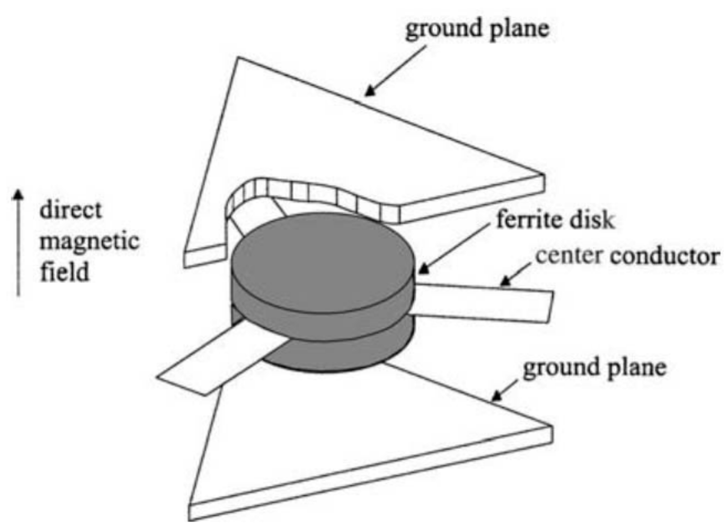


Fig 1: Schematic diagram of three-port stripline circulator

The gyro-magnetic material is magnetized perpendicularly to the plane of the device by a static magnetic field. A circulator condition is met whenever all three ports are matched. Circulation condition is established by operating between the two split frequencies. The impedance of the (+) mode, which has the higher resonant frequency, will have an inductive reactance component, and the (-) mode, which has the lower resonant frequency will have a capacitive reactance component. If the phase angles of the impedances of the two mode are 30^o at the operating frequency, then the standing wave pattern will be rotated 30^0 from that which obtains with no splitting of the modes. When two voltage maxima coincide at a 30^0 away from the input port, the rotation of the pattern is in the direction of rotation of the (+) mode. It states that magnetic biasing field $H_{dc} > H_{res}$ (ferromagnetic resonance field). When $H_{dc}<H_{res}$, the rotation of circulation is in opposite direction.

Three ports circulator is a matching network, thus reflection coefficient must be zero, and any power reflected from the load will be absorbed as opposed to being reflected back to the load. Therefore, one port of the circulator will be the isolate port.

FIELD THEORY

MAGNETIC FIELD

As shown in figure 2, the center of these connection are taken at φ value, -120^0, 120^0 and 0 for the input, output and decoupled. W is the width of the stripline at a typical port of the junction. It is assumed that the center conductor thickness t is zero. Ψ is known as the coupling angle of the circulator

$$\text{Sin}\psi = W/2R$$

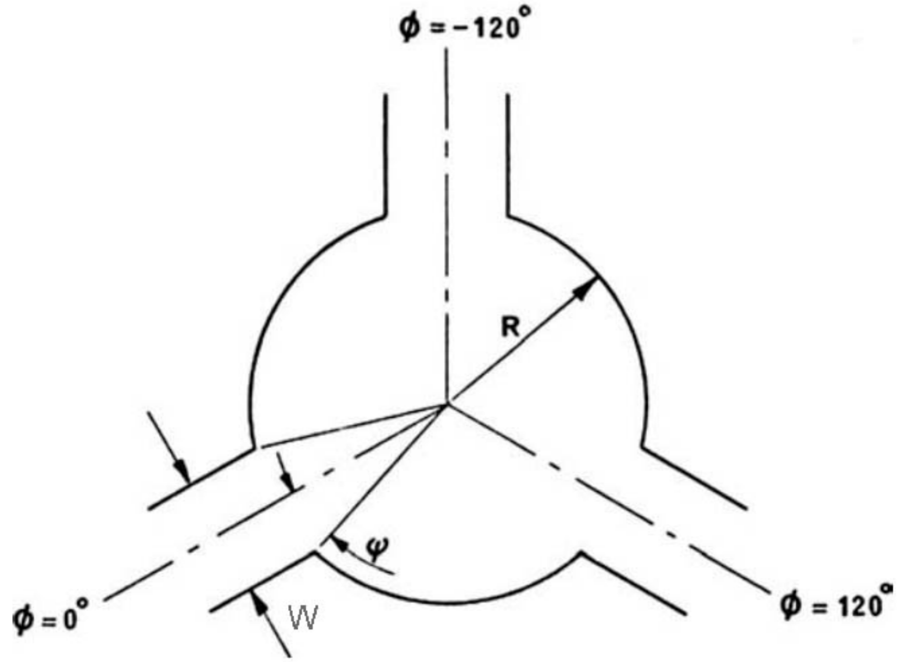


Fig 2: Schematic diagram of stripline circulator

The value of W should be not too large in comparison with R.

$$\frac{W}{R} < 0.75$$

Because of distribution of $H_\varphi(R,\Phi)$ and influence of the stray field, W must not be very small. From the boundary condition, the magnetic field is a constant over the width of each stripline and zero elsewhere. This can be expressed by

$$\left.\begin{array}{lr} -\psi < \phi < \psi, & H_\phi = H_1 \\ 120° - \psi < \phi < \psi + 120°, & H_\phi = H_1 \\ -120° - \psi < \phi < \psi - 120°, & H_\phi = 0 \\ \text{elsewhere}, & H_\phi = 0 \end{array}\right\}$$

and

$$\left.\begin{array}{ll} \phi = 0, & E_z = E_1 \\ \phi = 120°, & E_z = -E_1 \\ \phi = -120°, & E_z = 0 \end{array}\right\}$$

The electric field are taken as the average values of Ez over the ports at r = R and are assumed arbitrary elsewhere.

ELECTRIC FIELD

The electric field intensity in the disk is assumed to have a z-component only. The specific permittivity of the ferrite is denoted by ε and the gyrotropic permeability by μ.

$$[\mu] = \begin{bmatrix} \mu & -i\kappa & 0 \\ i\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

An effective permeability μ_{eff} and intrinsic wave number k can be introduced by

$$\mu_{eff} = (\mu^2 - \kappa^2)/\mu$$

$$k^2 = w^2 \mu_0\, \varepsilon_0\, \mu_{eff}\, \varepsilon$$

The electric field intensity in the disk $E_z(r, \Phi)$ must satisfies the homogeneous Helmholtz equation

$$\left[\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \phi^2}+k^2\right]E_r(r,\phi)=0$$

And the magnetic field intensity in the disk are related to $E_z(r, \phi)$ by

$$H_r = \omega\mu_0\mu_e j\left[\left(\frac{1}{r}\frac{\partial E_z}{\partial \phi}\right)-j\frac{\kappa}{\mu}\left(\frac{\partial E_z}{\partial \mathrm{r}}\right)\right]$$

$$H_\phi = \omega\mu_0\mu_e j\left[\left(\frac{\partial E_z}{\partial r}\right)+j\frac{\kappa}{\mu}\left(\frac{1}{r}\frac{\partial E_z}{\partial \phi}\right)\right]$$

Then a Green's function G(r,θ;R, θ') can be introduce such as

$$E_z(r,\theta)=\int_{-\pi}^{\pi}G(r,\theta;R,\theta')H_\phi(R,\theta')d\theta'$$

The Green's function can be expressed in term of Bessel function, disk radius, radial coordinate and intrinsic wave impedance

$$G(r\theta;R,\theta')=\frac{-jZeffJ_0(Sr)}{2\pi J'_0(SR)}+\frac{Zeff}{\pi}\sum_{n=1}^{\infty}\frac{\left(\frac{k}{u}\right)\left(\frac{nJn(SR)}{SR}\right)Sinn(\theta-\theta')-jJ'n(SR)Cosn(\theta-\theta')}{(J'n(SR))^2-\left[\left(\frac{k}{u}\right)\left(\frac{nJn(SR)}{(SR)}\right)\right]^2}Jn(Sr)$$

Jn (Sr): Bessel function of the first kind with order n

J'n (Sr): derivative of Jn (Sr) with respect to its argument

r: radial coordinate

R: disk radius

Zeff: effective intrinsic wave impedance of the ferrite, $Z_{eff}=\sqrt{\frac{\mu_0\mu_{eff}}{\varepsilon_0\varepsilon}}$

INPUT WAVE IMPEDANCE

Let the characteristic impedance of the stripline be Zin, and it is easily derived by

$$Zin = -Zd + \left(\frac{j2Zeff}{\pi}\right)\left(\frac{C_1^3 + C_2^3 + C_3^3 - 3C_1C_2C_3}{C_1^2 - C_2C_3}\right)$$

With

$$C_1 = \frac{\psi B_0}{2A_0} + \sum_{n=1}^{\infty}\left(\frac{Sin^2 n\psi}{n^2\psi}\right)\frac{AnBn}{A^2n - \left(\frac{n\kappa}{\mu SR}\right)^2 B^2n} - \frac{\pi Zd}{j2Zeff}$$

$$C_2 = \frac{\psi B_0}{2A_0} + \sum_{n=1}^{\infty}\left(\frac{Sin^2 n\psi}{n^2\psi}\right)\frac{AnBnCos\left(\frac{2\pi n}{3}\right) - \left(\frac{jn\kappa}{\mu SR}\right)B^2nSin\left(\frac{2\pi n}{3}\right)}{A^2n - \left(\frac{n\kappa}{\mu SR}\right)^2 B^2n}$$

$$C_3 = \frac{\psi B_0}{2A_0} + \sum_{n=1}^{\infty}\left(\frac{Sin^2 n\psi}{n^2\psi}\right)\frac{AnBnCos\left(\frac{2\pi n}{3}\right) + \left(\frac{jn\kappa}{\mu SR}\right)B^2nSin\left(\frac{2\pi n}{3}\right)}{A^2n - \left(\frac{n\kappa}{\mu SR}\right)^2 B^2n}$$

$$An = J'n(SR)$$
$$Bn = Jn(SR)$$

The real part of Zin does not depend on frequency, but the imaginary part does.

SCATTERING MATRIX

Stripline circulator is a 3 ports matching and lossless network.

$$S=\begin{pmatrix} \alpha & \gamma & \beta \\ \beta & \alpha & \gamma \\ \gamma & \beta & \alpha \end{pmatrix}$$

If the reflection coefficient $|\alpha| << 1$, the equations

$$|\gamma| = |\alpha|, \qquad |\beta| = 1-2|\alpha|^2$$

The elements of S satisfy the equations

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 = 1$$
$$\alpha\beta^* + \alpha\gamma^* + \beta\gamma^* = 0$$

Then,

$$S=\begin{pmatrix} \alpha & \alpha & 1-2\alpha^2 \\ 1-2\alpha^2 & \alpha & \alpha \\ \alpha & 1-2\alpha^2 & \alpha \end{pmatrix}$$

When circulator is perfect match network, $|\alpha| = 0$,

Therefore

$$S=\begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

S matrix equations design

$$\alpha = 1-\left(\frac{\pi Zd(C_1^2 - C_2C_3)}{jZeff(C_1^3 + C_2^3 + C_3^3 - 3C_1C_2C_3)}\right)$$

$$\beta = \left(\frac{\pi Zd(C_2^2 - C_1C_3)}{jZeff(C_1^3 + C_2^3 + C_3^3 - 3C_1C_2C_3)}\right)$$

$$\gamma = \left(\frac{\pi Zd(C_3^2 - C_1C_2)}{jZeff(C_1^3 + C_2^3 + C_3^3 - 3C_1C_2C_3)}\right)$$

DESIGN CIRCULATOR

I chose manganese ferrite aluminate as ferrite material which was used in this design. The thickness of each ferrite disk is 5.5mm. The simulation parameters of the ferrite are: the dielectric constant ε=14.2, delta magnetic field ΔH =150 Oe and the saturation magnetization $4\pi M_s$=1750 Gauss. Based on the theory of stripline circulators, the stripline circulators are designed firstly and then optimized using high frequency structure simulation (HFSS) software.

We have derived the radius of central conductor and ferrite disk *R*=30mm from the material physic parameters. The width of transmission line W=15mm. The operation frequency f = 915MHz. Fig. 3 shows dimension of stripline circulator design

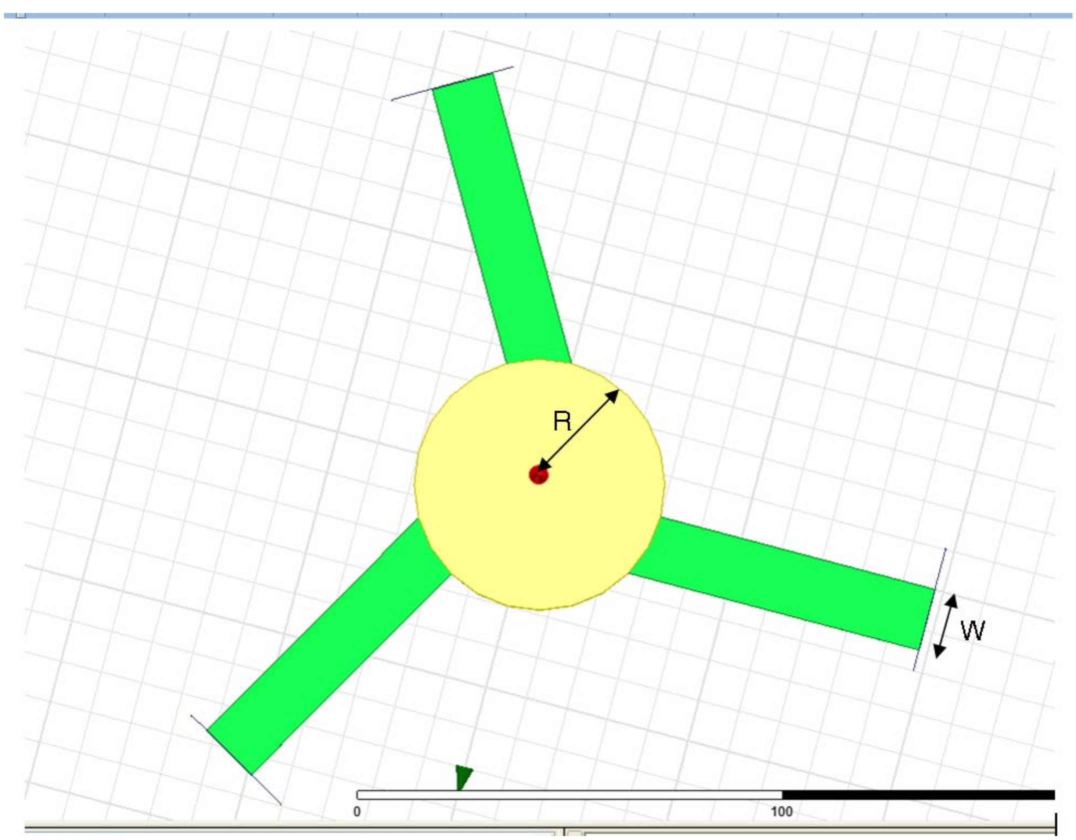


Fig 3: Schematic diatram of stripline circulator

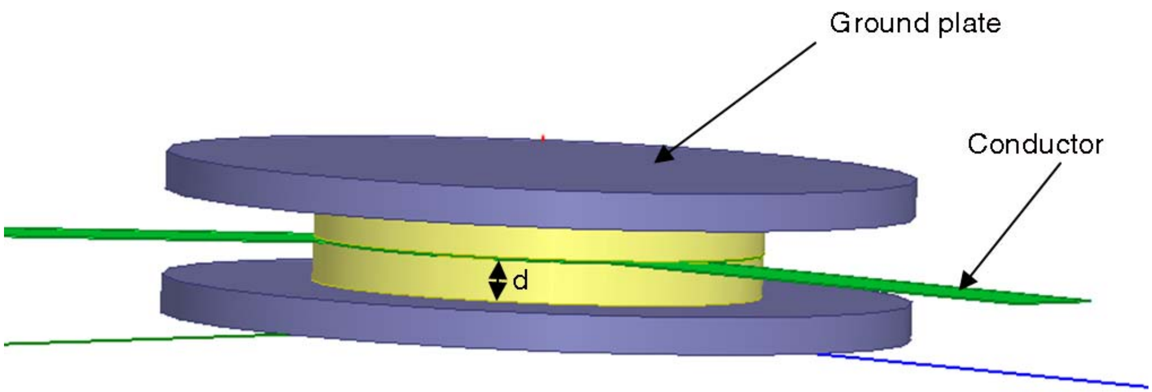


Fig 4: 3D model of stripline circulator

APPROXIMATE CIRCULATION DESIGN

From frequency f = 915MHz, we can calculate wavelength λ=32.7cm by $\lambda=\frac{c}{f}$, With c= $3x10^8$

The width of stripline is restricted in accordance with W< λ/30.

And $\frac{W}{R}$<0.75 for ε≈ 14

Internal magnetic field Hi and R can be calculate by equations

$$Hi = \sqrt{\frac{\lambda}{\sqrt{3W}} Ho.4\pi M} \text{-} 4\pi M$$

$$\frac{R}{\lambda} = \frac{1.84}{2\pi\sqrt{\varepsilon}}\sqrt{\frac{Hi}{Hi + 4\pi M}}$$

Hi =1501 gauss

Ho = $\frac{\omega}{\gamma}$= 160, with γ= 2π x 2.8MOe

and

$$m = \left(\frac{4\pi Ms}{Ho}\right)$$

$$h = \frac{Hi}{Ho}$$

$$s = \frac{\Delta H}{Ho}$$

We have, $h = 9.38$ (h^2>>1)

$s = 0.937$

$m = 10.937$

Thus, relative permeability $\mu_{eff} = \frac{(h+m)}{h}$ = 2.17

κ, μ: Polder tensor components

κ/μ <<1

$$\mu = 1 + \left(\frac{hm(h^2 - 1)}{(h^2 - 1)^2 - s^2}\right)$$

$$\kappa = \left(\frac{m(h^2 - 1)}{(h^2 - 1)^2 + s^2}\right)$$

$$\frac{\kappa}{\mu} = 0.057$$

Conductivity of stripline

$$\sigma = |\gamma|\frac{Hi}{\omega} = 0.731 < 1$$

⇨ The circulator operate at below resonance

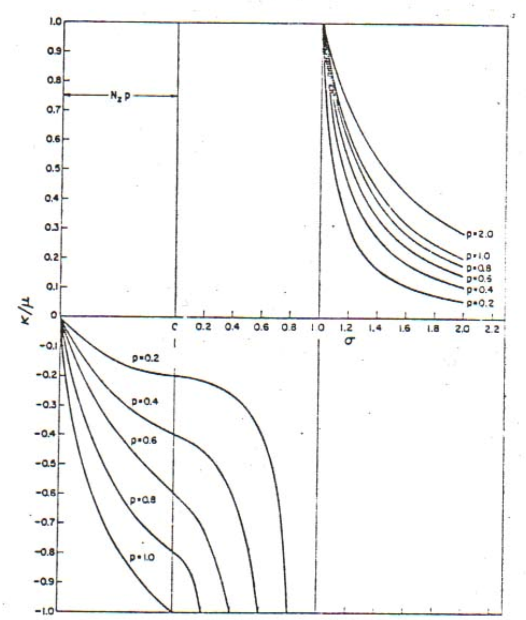
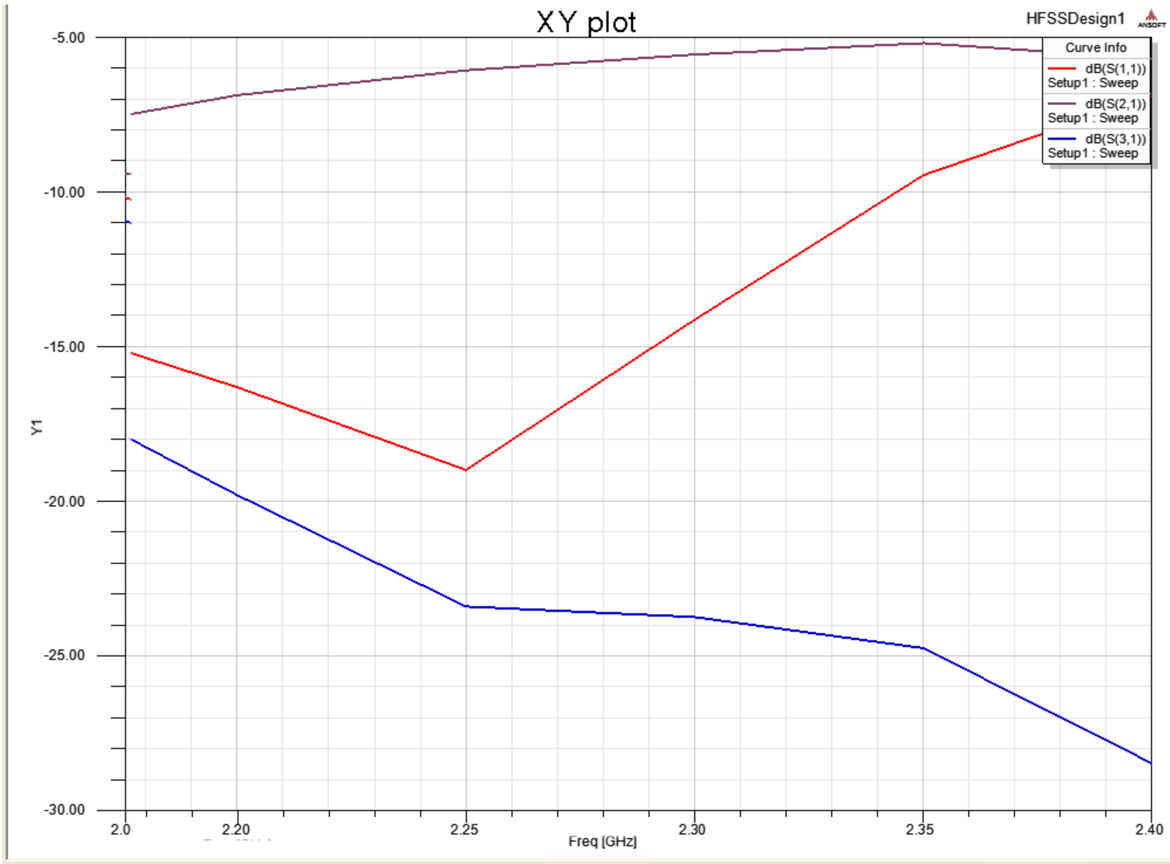


Fig. 5. κ/μ vs. σ, where $\sigma = |\gamma| H_{int}/\omega$.

From Fig 5, that we can obtain the junction circulator has biasing field in the ferrite below resonance (σ<1). Below resonant frequency, the series resonant circuit look capacitive since the impedance of the capacitor increase to the value greater than the decreasing inductive reactance. Above resonance, the inductive reactance increase, capacitive reactance decrease. Most Y circulator in use at the present time employ the below resonance type of operation. Above resonance operation requires smaller disk diameter, a higher saturation and biasing field, and larger magnet.

RESULT

HIGH FREQUENCY SIMULATION STRUCTURE (HFSS)



$$dB = -20\log|S|$$

Resonance at 2.25 GHz

$S_{11} = -19dB$ => $S_{11} = 0.05$ %error = $\frac{experimental - theory}{theory} \times 100\% = 5\%$

$S_{21} = -6dB$ => $S_{21} = 1.2$, %error = $\frac{1.2-1}{1} \times 100\% = 20\%$

$S_{31} = -23dB$ => $S_{31} = 0.13$ %error = 13%

IMPROVEMENT

The manufacture of ferrite production do not have customize option for the size and ferrite material. Therefore, I cannot build prototype. I will follow the project in the summer. The twenty percent of error is a high value in this result. These are two improvement that I should cover in the future; change permeability ferrite material ($1<\mu_{eff}<1.5$) and use transmission line conductor which has higher conductivity.

CONCLUSION

The operation of the ferrite junction circulator has been explained on the basic of split resonance of the junction in which the standing wave pattern of the resonator is rotated to produce a null or no coupling at the isolated port. A design procedure using the quarter wave transformer for matching stripline circulator has been outlined. The ferrite is useful only where the radio frequency field approach circular polarization. Other symmetrical junction which have been used are simple 120^0 stripline junction with a circular disk, triangular junctions of both ferrite and center conductor.

I would like to special thank you Dr Ray Kwork who gave me great ideas, materials and feedbacks about this project.

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