A Study on the Design of Coaxial Isolator with Filter Circuit

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Abstract

In this paper, the detailed design of the 1.8 GHz band Y-junction stripline circulator with the low pass filter circuit in the center conductor in order to higher attenuations below value of -30 dB at 3rd order harmonics is proposed and presented. The HFSS is used to simulate designed 1.8GHz band circulator to check the non-reciprocal characteristics at operating frequency range and the results are compared with the experiment data. From these measurement results, We confirm that the proposed Y-junction stripline circulator using center conductor with filter circuit is effective in achieving very high attenuations below of -30 dB at 3rd order harmonics.

Keywords: *Isolator, Ferrite, Attenuation*

1. Introduction

The RF/Microwave Y-junction isolator has three-port and is one of the non-reciprocal devices and can be use as switch well as isolator. The strip-line Y-junction circulator has been studied since the mid of 1960's [1-4],[8]. Auld[1] has considered the theory of circulators in terms of S-parameter of devices. Davis[2] have applied that concepts in the design of circulator. Boson[3] has made an analysis of the circulator in terms of the normal mode of the center disk. And Comstock[4] proposed the operation of the circulator in terms of counter-rotating normal mode. Simon[5] has studied the design of the circulator in below resonance. However, all of the study of the RF/Microwave circulator are focused in low loss and high attenuation at operating frequency region and are focused in the study of the shape of circulator such as drop-in, coaxial, microstrip type, strip type and lumped type[6],[8]. Therefore the specifications of the circulator at 3rd harmonic band are not considered.

At the present, a number of communication systems such as CDMA, PCS, Wimax and WCDMA are serviced. So the quality of the call is bad when the environment of the electromagnetic wave is gradually aggravated. Especially, because the circulator of transmit system in the base station is nonlinear device, the harmonic specifications including the inter-modulation signal is poor. Finally, the harmonic signal such as 3 rd harmonic inside circulator must be suppressed.

In this paper, the 1.8GHz band strip-line circulator using the center conductor with low pass filter circuit in order to obtain high attenuation of 30 dB at 3 rd harmonic band where it is a reciprocal region of circulator is designed. And in order to verify the non-reciprocal specification at operating frequency band, The HFSS(High Frequency Structure Simulator) is used.

The designed circulator is manufactured and is measured using the HP 8753D Network analyzer and the result of measurement be compared to simulation data. The designed circulator using center conductor with filter circuit has the attenuation of 30 dB at 3rs harmonic band without a change in the specification at operating frequency range.

2. Theoretical Review

2.1. Characteristic of the Ferrite

The characteristics of ferrite are based on the magnetic dipole. That is an electron spin. The electron spin motion is presented in Fig. 1 and The magnetic dipole momentum from electron spin is the following (1).

$$m = \frac{qh}{2m_e} = 9.27 \times 10^{-24}\ \mathrm{Am^2} \tag{1}$$

where, h is Plank constant.

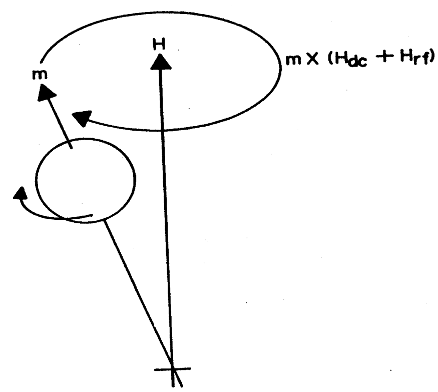


Fig.1.The electron spin in magnetic field

The ratio of spin angular moment and magnetic moment is the following (2).

$$\gamma = \frac{m}{s} = \frac{q}{m_e} = 1.759 \times 10^{11}\ {}^{C}\!/_{Kg} \tag{2}$$

where, s = h/2 , the spin angular moment.

Now the motion equation of electron spin is presented by the following (3).

$$\begin{aligned} \frac{dM_x}{dt} &= -\omega_0 M_y + \omega_m H_y \\ \frac{dM_y}{dt} &= \omega_0 M_x - \omega_m H_x \\ \frac{dM_z}{dt} &= 0 \end{aligned} \tag{3}$$

where, $\omega_0 = \mu_0 \gamma H_0$and $\omega_m = \mu_0 \gamma M_s$.

Therefore the final motion equation could be presented by the following (4)

$$\frac{d^2 M_x}{dt^2} + \omega_0^2 M_x = \omega_m \frac{dH_y}{dt} + \omega_0 \omega_m H_x \tag{4a}$$

$$\frac{d^2M_y}{dt^2} + \omega_0^2 M_y = -\omega_m \frac{dH_x}{dt} + \omega_0\omega_m H_y \tag{4b}$$

When the ferrite is magnetized by external field, the tensor permeability, [μ] could be expressed by the following (5), (6)

$$[\mu] = \begin{pmatrix} \mu & -jk & 0 \\ jk & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5}$$

where, $\mu = \frac{\mu_0\gamma^2 H_0 M_s}{\omega_0^2-\omega^2}$, $k = \frac{\gamma\omega M_s}{\omega_0^2-\omega^2}$, $\mu_0 = 4\pi X10^{-7}$H/m, $\omega_0 = \gamma\mu_0 H_0$.

For Above-resonance, $\omega_0^2 \ll \omega^2$ the effective permeability, μ_{eff} is

$$\mu_{eff} = \frac{H_0+M_0}{H_0} \tag{6}$$

Therefore the two counter-rotating wave in the magnetized ferrites are (7) and (8). There are different phase constant and the operating frequency is between two resonance frequency[3],[7].

$$\Gamma_+ = j\omega(\mu_0\varepsilon)^{0.5}\left(\frac{\mu^2-k^2}{\mu}\right)^{0.5} \tag{7}$$

$$\Gamma_- = j\omega(\mu_0\varepsilon)^{0.5} \tag{8}$$

Finally, the circulator use ferrite with (5) ~ (8) and then have non-reciprocal operation.

2.2. The Theory of Circulator

In general, The RF and microwave band Y-junction circulator has compose of ferrites, center conductor, external magnet and grounds as the following Fig(2).

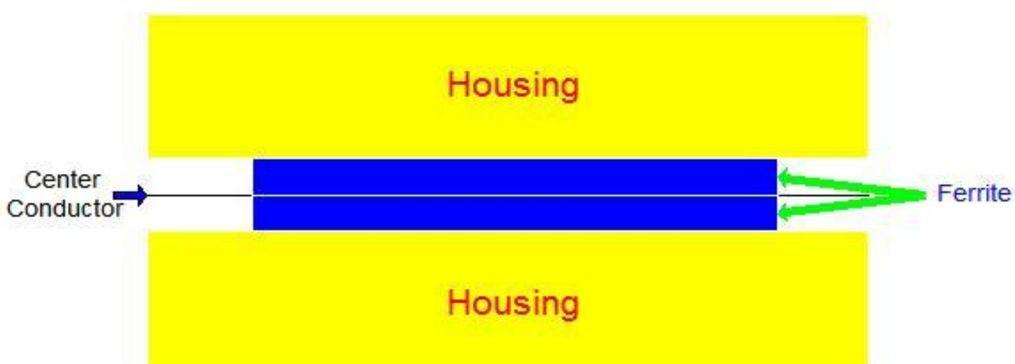
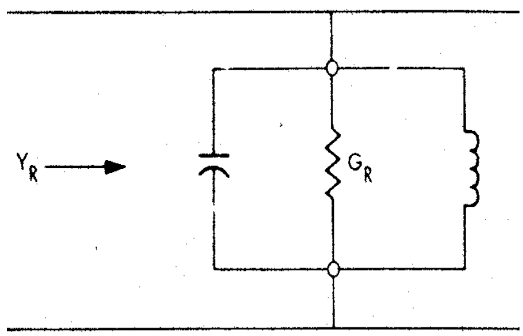


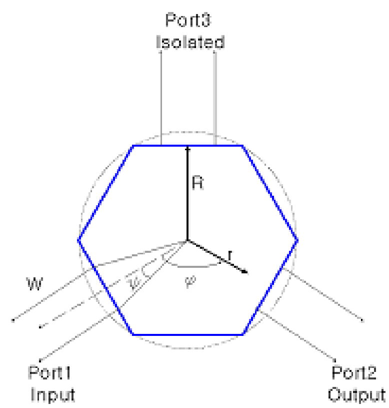
Figure 2.The inside schematic diagram of the circulator/isolator

In order to study the theory of circulator, the equivalent circuit and model is presented in Fig. 3 [4]. The shape of ferrite select hexagonal one in order to obtain lower insertion loss and the ferrite is approximated disk shape in the analysis.

In case of the input wave Admittance, ψ is a small, it is as following [3].



(a) Equivalent Circuit



(b) Theoretical model

Figure 3.The resonator equivalent circuit and theoretical model of the isolator

$$Y_m = G_R \cong \frac{Y_{eff}\left|\frac{k}{\mu}\right|}{\sin\varphi},\ Y_{eff} = \sqrt{\frac{\varepsilon\varepsilon_0}{\mu_0\mu_{eff}}} \tag{9}$$

where, G_R the conductance of output strip-line. Also, Loaded-Q, Q_L is presented,

$$Q_L = 1.48\frac{\omega R^2\varepsilon\varepsilon_0}{G_R d} \tag{10}$$

where, d is the thickness of ferrite [4].

For without loss, magnetic-Q(Q_μ) is given by

$$Q_u = \frac{1-(\frac{k}{\mu})^2}{\left[1+(\frac{k}{\mu})^2\right]\alpha\frac{k}{\mu}} \tag{11}$$

where, $\alpha = \gamma\Delta H/2\omega$. The total unloaded-Q (Q_0) is given by

$$\frac{1}{Q_0} = \frac{1}{Q_u} + \frac{1}{Q_e} \tag{12}$$

where, $Q_e = \frac{1}{\tan\delta}$
Then the insertion loss can be obtained [4].

$$\text{Insertion Loss} = 10\log_{10}(1-\frac{Q_L}{Q_o}) \tag{13}$$

Also, the radius of ferrite, R is given by

$$R = \frac{1.84\lambda}{2\pi\sqrt{\mu_{eff}\varepsilon}} \tag{1}$$

where, μ_{eff} is effective permeability and is same as (6).
And the frequency bandwidth can be presented in terms of $\frac{k}{\mu}$,

$$\frac{f_2 - f_1}{f_0} = 2.9\frac{k}{\mu}\rho \tag{2}$$

where, ρ is a maximum reflection constant.
Then, when using the above equation of (15), $\frac{k}{\mu}$ can be calculated approximately.

3. The Design of Isolator

The specifications of circulator are presented in table 1. The radius of ferrite is calculated using (14) and the value is 9.9 mm.

Table 1.The specifications on the isolator

Frequency range	1,805 ~1,880 MHz
Insertion loss	0.2 dB
V.S.W.R.	1.15 : 1
Isolation	25 dB
Attenuation @3f_o	30 dB

Table 2. The chracteristics value of the selected ferrite

$4\pi M_s$	0.16 T
ε_r	14.7
ΔH@-3dB	< 12
tanδ	≤ 0.0002
T_c	220

The value of $4\pi M_s$is 0.16T and the thickness of ferrite is 1.5 mm. The characteristic values of the selected ferrite are presented in table 2.

In order to satisfy the specifications in the table 1, the admittance Y_R of Fig. 4(a) may be expressed as

$$\mathrm{VSWR} \cong \frac{\left|{Y_R}^2\right|}{{G_R}^2} \cong \sec^2\theta \tag{3}$$

when the value of θ is selected, loaded-Q, Q_L can be obtained using (10). And using the (11) ~ (15). the specification value of the circulator can be calculated and expressed in table 3.

Table 3.The calculated characteristic value of the circulator

Factor	Specification
Q_L	12.11
k/μ	0.215
μ_{eff}	1.5
R	9.9 mm
G_R	0.012 mho
I/L	-0.011 dB

The schematic of center conductor circuit are presented in Fig. 3. It have a same resonant dimension as a ferrite's radius of 9.9 mm. The low pass filter circuit is designed to have attenuation of 30 dB at 3 rd harmonic band using the (17).

$$n = \frac{\log_{10}(\log_{10}^{\left[\frac{L(\omega)}{10}\right]} - 1)}{2\log_{10}^{(\frac{\omega}{\omega c})}} \tag{4}$$

Using the (18), the element value, g of the filter circuit can be calculated and are presented in the table 4.

$$g_0 = 1,\quad g_{k+1} = 1,\qquad g_k = 2\sin\left[\frac{(2k-1)\pi}{2n}\right], k = 1,2,\cdots,n\,. \tag{5}$$

Table 4.The calculated element value g

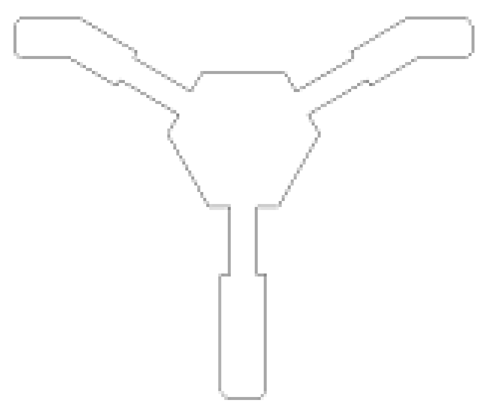
	g_0	g_1	g_2	g_3	g_4	g_5	g_6
n=5	1	0.618	1.618	2.0	1.618	0.618	1

Using the calculated value of g and characteristic impedance, the Inductance and Capacitance are following as, it was shown in [9] :

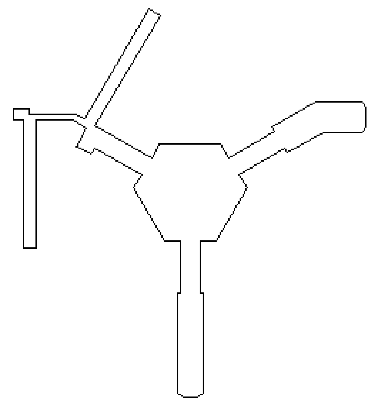
$$L_k = g_k\left(\frac{Z_o}{\omega_1{}'}\right),\quad C_k = g_k\left(\frac{1}{\omega_1{}'Z_o}\right) \tag{6}$$

where, ω_1' is cut-off frequency.

The center conductor without filter circuit is presented in Fig. 4(a) and the center conductor with filter circuit is presented in Fig. 4(b). The strip-line filter has a height of 3.2 mm, a thickness of 0.2 mm, the capacitance, C = 0.9mm X 11.5mm(width X length), the inductance , L= 0.6mm X 4.2mm(width X length) and the total length are 13.5 mm.



(a) Without low pass filter



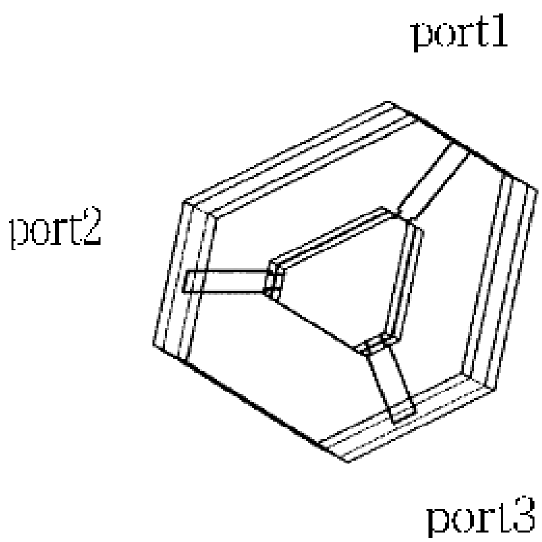
(b) With low pass filter

Figure 4.The circuit of center conductor

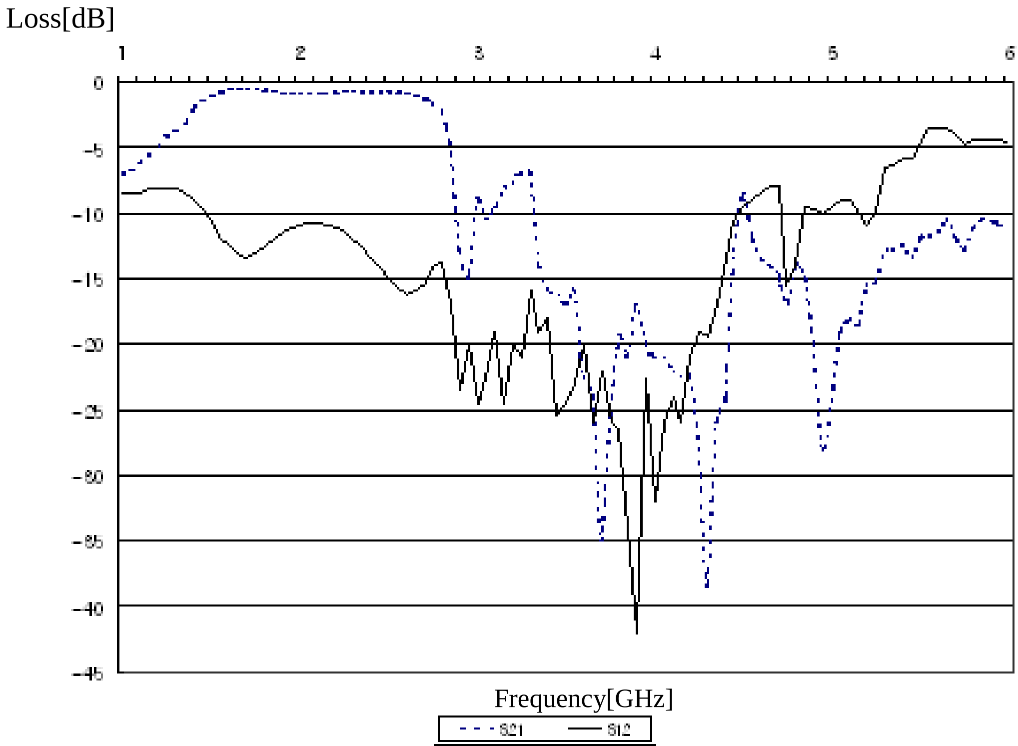
4. The Simulation of Circulator

In the simulation of the circulator, The HFSS of ANSOFT is used. The schematic of circulator is presented in Fig. 5(a). And the result of simulation can be shown in Fig. 5(b). It was proposed for the ferrite to be magnetized by uniform external field. And the $4\pi M_s$ of ferrite is 0.16 Tesla. The permittivity and tan δ of ferrite are 14.7 and 0.0002 respectively.

In Fig. 5(b), The S-parameter, S_{21} and S_{12} in the resonant frequency region, 1,805 ~ 1,880 MHz, can be known as non-reciprocal feature.



(a) Modeling



(b) Simulation result

Figure 5. The simulation results without stub-filter

In Addition, because the position of filter is out of resonator of ferrite, as Fig. 4(b), the change of characteristic by filter circuit in the operating frequency range do not appear almost.

5. The Experiment Data

The designed circulator was manufactured and was measured using the HP 8753D Network analyzer. The manufactured circulator has a housing of AL in order to get perfect ground and has a cover of steel in order to get shield from magnetic field. The photo of the circulator is presented in Fig.6.

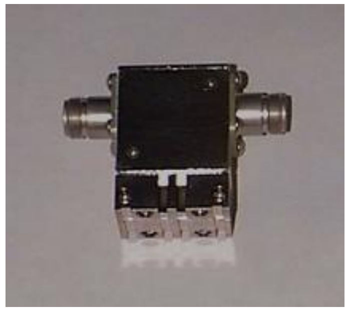


Figure 6.The photo of the Isolator

The measurement results of circulator using conductor without filter circuit are presented in Fig. 7. Also In case of conductor with filter circuit, the results are presented in Fig. 8.

For S_{12} in the operating range, the simulation data was -13 dB and the measurement data was -25 dB. The different value of S_{12} comes from the assumption that the ferrite was magnetized by uniformed magnetic field in the step of simulation.

In Addition, the characteristic change by filter circuit : the insertion loss without filter circuit in operation frequency range was -0.075 dB. With filter circuit, the insertion loss was -0.12 dB.the isolation and insertion loss value without filter in 3 rd harmonic range was about -4dB ~ -7dB and the isolation and insertion loss with filter circuit was -30 dB. Therefore, it can obtain higher attenuation of -30dB using center conductor with filter circuit.

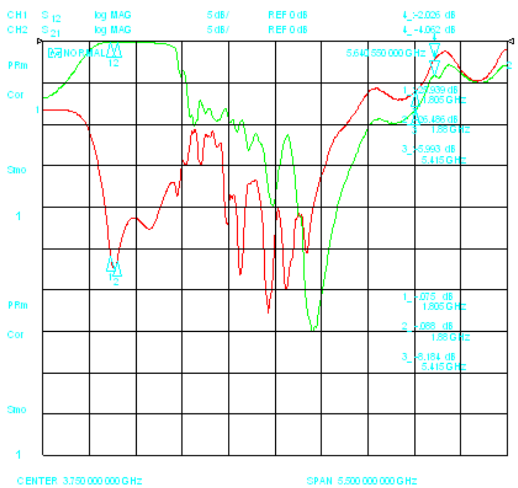


Figure 7.The S-parameters of the isolator without stub-filter

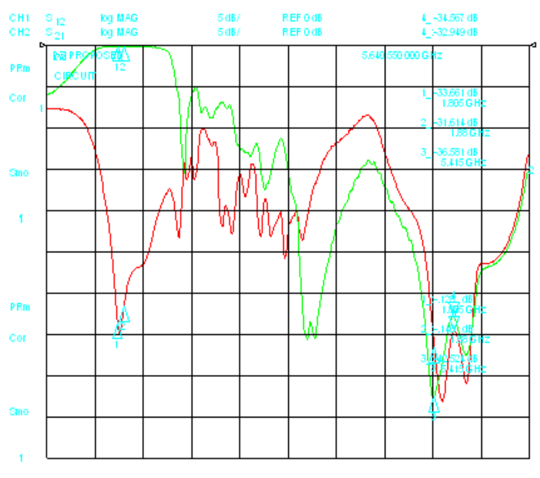


Figure 8.The S-parameters of the isolator with stub-filter

And the frequency shift amount according to the saturation magnetic field of the ferrite is presented in the table 5. The $4\pi M_s$ is decreased from 0.16 T to 0.12 T.

Table 5.The frequency shift amount according to $4\pi M_s$

$4\pi M_s$ (Tesla)	0.12	0.13	0.14	0.15	0.16
Frequency Shift (GHz)	△1.2	△0.9	△0.7	△0.4	△0

6. Conclusion

In this paper, the 1.8GHz band strip-line circulator using the center conductor with low pass filter circuit in order to obtain high attenuation of 30 dB at 3rd harmonic band where it is a reciprocal region of circulator is designed. The results of measurement are following. The transmission parameters at the operating frequency band have a same characteristic as conventional center conductor without filter circuit. However, $S_{21,}$ the transmission characteristics, of proposed isolator using the center conductor with filter circuit at 3rd harmonic band have a higher attenuation of 20 dB.

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