Improved Lumped-Element Two-Port Isolator

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Abstract — **In a lumped-element two-port isolator, the relationship between the angle ϕ across two central conductors and electric characteristics is revealed using circuit analysis. At ϕ=90 degree, high isolation loss is achieved. At ϕ=60 degree, the bandwidth of insertion loss becomes maximum. This theoretical prediction at ϕ=60 degree was confirmed qualitatively by 360MHz band experiments. Furthermore, we obtained the interesting result that the perfect isolation conditions at ϕ=60 degree is quite similar to three-port circulator conditions.**

I. Introduction

In 1977, lumped-element two-port isolator was proposed by Hodges et al[1]. Since then, the several corresponding patents [2][3] were submitted.

As shown in Fig.1, this structure has a ferrite disk wound with two perpendicularly crossed central conductors, L_1 and L_2 , of which each one end is connected to ground, the other end to input and output port. The static magnetic field is applied perpendicularly to the ferrite disk plane. The matching capacitors C_1 and C_2 are connected between each port and ground. The resistance R for energy absorption is connected between input and output ports. This configuration has an advantage of simple structure that one central conductor and one matching capacitor are eliminated, comparing with a conventional three port circulator with resistance R. If we succeed in developing a broadband and low loss tow-port isolator, the cost reduction would occur effectively.

However, the practical usage of this type isolator has not been reported until the recent research[4]. The reasons are not only because a low loss and broadband two-port isolator was not realized experimentally but also the circuit analysis of two-port isolator could not be studied to make the experimental procedure clear.

In this paper, the admittance matrix of two-port isolator will be derived at first. The approach to make a circuit simulator directly related to S-parameters from the admittance matrix will be introduced. Through this procedure, we derive the perfect isolator conditions corresponding to various cross-angles ϕ between two central conductors. The theoretical predictions will be proved in experiments.

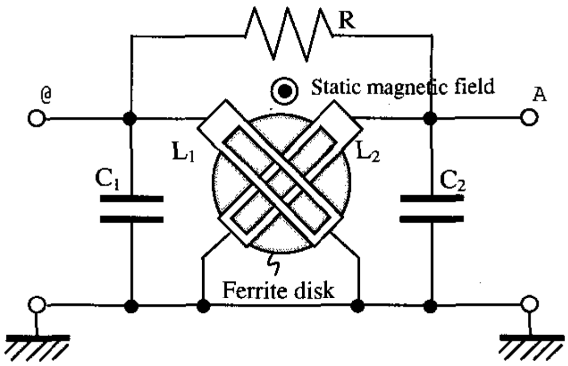

Fig.1 Basic structure of lumped-element two-port isolator

II. ADMITTANCE MATRIX

Before deriving the whole admittance matrix of Fig.1, we introduce the impedance matrix of the ferrite disk portion wound with two central conductors with cross-angle ϕ shown in Fig.2.

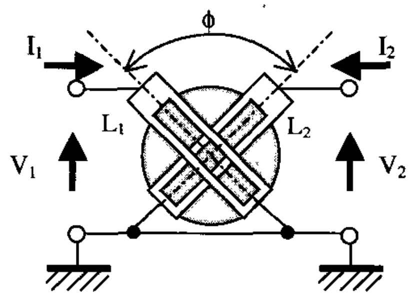

Fig.2 Current and voltage definitions.

In this case, the impedance matrix (1) and its elements (2) are expressed as follows;

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$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (1)$$

$$\left. \begin{array}{l} Z_{11}=j\omega\, \mu_{xx}K_{11} \\ Z_{22}=j\omega\, \mu_{xx}K_{22} \\ Z_{12}=\omega\, \{ \mu_{xy}\sin\phi + j\, \mu_{xx}\cos\phi \}K_{12} \\ Z_{21}=\omega\, \{ -\mu_{xy}\sin\phi + j\, \mu_{xx}\cos\phi \}K_{21} \end{array} \right\} \quad (2a)$$

$$\left. \begin{array}{l} \mu_{xx}= (\mu_p+\mu_n)/2 \\ \mu_{xy}= (\mu_p-\mu_n)/2 \end{array} \right\} \quad (2b)$$

where μ_p, μ_n correspond to positive and negative circular polarization permeability respectively.

Therefore the admittance matrix elements are expressed as follows;

$$\left. \begin{array}{l} Y_{11}=Y_{22}=Z_{11}/\Delta \\ Y_{12}= -Z_{12}/\Delta \\ Y_{21}= -Z_{21}/\Delta \end{array} \right\} \quad (3a)$$

$$\Delta = -(\omega \sin\phi\, K)^2(\mu_{xx}^{\ 2}-\mu_{xy}^{\ 2}) \quad (3b)$$

Here, assuming the symmetrical structure of two central conductors and the perfect coupling between them, we adopted the relations; $K_{11}=K_{22}=K_{12}=K_{21}=K$ A$C_1=C_2=C$.

Next, we'd like to obtain the whole admittance matrix in Fig.1. In this paper, the cross-angle ϕ between two central conductors are determined arbitrary. Along with this, the perfect isolation condition will require some compensation by adding a parallel capacitor, C_w, and inductor, L_w, as shown in Fig.3.

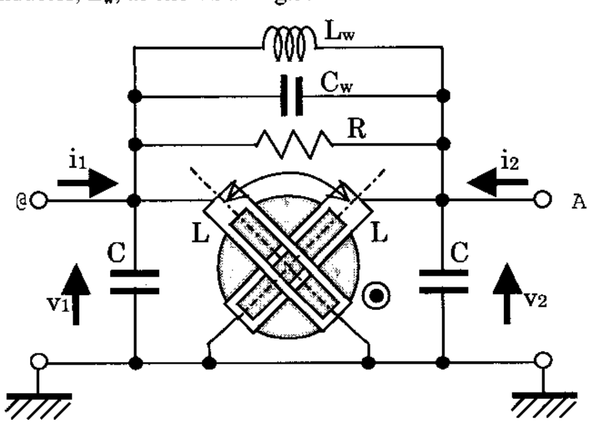

Fig.3 Fundamental circuit for calculating a whole admittance matrix.

As the results, the admittance matrix elements are derived as follows;

$$\left. \begin{array}{l} y_{11}=y_{22}=1/R+j\{\omega(C+C_w+K/\Delta)-1/(\omega L_w)\} \\ y_{12}= -1/R - \omega \sin\phi\, K\mu_{xy}/\Delta \\ \qquad -j\{\omega(C_w+\cos\phi\, \mu_{xy}/\Delta)-1/(\omega L_w)\} \\ y_{21}= -1/R+\omega \sin\phi\, K\, \mu_{xy}/\Delta \\ \qquad -j\{\omega(C_w+\cos\phi\, \mu_{xy}/\Delta)-1/(\omega L_w)\} \end{array} \right\} \quad (4a)$$

$$\Delta= -(\omega \sin\phi\, K)^2(\mu_{xx}^{\ 2}-\mu_{xy}^{\ 2}) \quad (4b)$$

The S-parameters are immediately calculated from the above equations.

III. FUNDAMENTAL EQUATIONS OF TWO-PORT ISOLATOR

The two-port isolator should have an ideal performance under the following conditions.

$$\left. \begin{array}{l} S_{12}=0 \longrightarrow y_{12}=0 \\ S_{11}=0 \longrightarrow y_{11}=1/R \\ S_{21}=1 \end{array} \right\} \quad (5)$$

1) From the condition of $y_{12}=0$, both of real and imaginary part of it should be zero. Then the following equations are obtained.

$$2\omega\, K \sin\phi/R=(1/\mu_n) - (1/\mu_p) \quad (6a)$$

$$\omega C_w - (1/\omega L_w)= \{\cos\phi/(2\omega\, K \sin^2\phi)\}\{(1/\mu_n) + (1/\mu_p)\} \quad (6b)$$

The right branch of (6b) changes the sign at ϕ=90 degree. When the right side is +, the left side needs C_w and when the right is −, the left needs L_w. Both terms don't coexist at the same time.

2) From the condition of $y_{11}=1/R$, the real part of it should be 1/R and the imaginary part should be zero. Then the following equations are obtained.

$$R=Z_o \quad (7a)$$

$$C=\{(1-\cos\phi)/(2\omega^2 K \sin^2\phi)\}\{(1/\mu_n) + (1/\mu_p)\} \quad (7b)$$

The resistance R has to be Z_o which is a characteristic impedance of measurement system.

In order to accomplish the perfect operation of two-port isolator, the above four equations have to hold simultaneously.

In the special three cases of ϕ=90, ϕ=60, ϕ=120 degree,

the above equations can be modified as follows;
(1) At ϕ=90 degree

$$\left.\begin{array}{l} 2\omega K/R=(1/\mu_n)-(1/\mu_p) \\ C=\{1/(2\omega^2K)\}\{(1/\mu_n)+(1/\mu_p)\} \\ C_w=0 \quad L_w= \end{array}\right\} \tag{8}$$

(2) At ϕ=60 degree

$$\left.\begin{array}{l} \sqrt{3}\omega K/R=(1/\mu_n)-(1/\mu_p) \\ C=\{1/(3\omega^2K)\}\{(1/\mu_n)+(1/\mu_p)\} \\ C_w=C \quad L_w= \end{array}\right\} \tag{9}$$

These relations are completely similar to the operation conditions of a conventional three-port circulator.

(3) At ϕ=120 degree

$$\left.\begin{array}{l} \sqrt{3}\omega K/R=(1/\mu_n)-(1/\mu_p) \\ C=\{1/(\omega^2K)\}\{(1/\mu_n)+(1/\mu_p)\} \\ C_w=0 \quad (1/L_w)=\{1/(3K)\}\{(1/\mu_n)+(1/\mu_p)\} \end{array}\right\} \tag{10}$$

IV. RESULTS OF SIMULATION

Fig.4 shows the calculated frequency dependence of S-parameters of the isolator for ϕ=90, ϕ=60 and ϕ=120 degree with which central frequency f_o is 1000MHz, based on above-mentioned admittance. Other design parameters are assumed that air-core inductance K=1[nH], 4πMs(of garnet)=900[G] and characteristic impedance Z_o =50[Ω].

Here, the specific bandwidth w[%] is defined as $w=(\Delta f/f_o)\text{x}100[\%]$, where Δf is the 20[dB] bandwidth of return loss S_{11} in Fig. 4(a). The insertion loss S_{21} at $0.9f_o$ in Fig.4(b) is referred as IL. The isolation loss S_{12} at $0.96f_o$ in Fig.4(c) is referred as IS.

The bandwidth of return loss S_{11} and insertion loss S_{21} becomes wider when ϕ becomes smaller as shown in Fig.4(a)(b). As shown in Fig.4(c), the isolation loss S_{12} at ϕ=90 degree has an extreme large value more than 45[dB] over the wide frequency range $0.9f_o$-$1.1f_o$. This is a typical feature of two-port isolator. Either at f<90 degree or at f>90 degree, the isolation loss S_{12} will degrade.

The parallel inductance L_w becomes infinite at ϕ=90 degree. Therefore, at the region of ϕ>90 degree, we calculated series resistance R_s and inductance L_s equivalent to R and L_w as shown in Fig.5. At ϕ=90 degree, the calculations become available due to R_s=50[Ω] and L_s=0[nH].

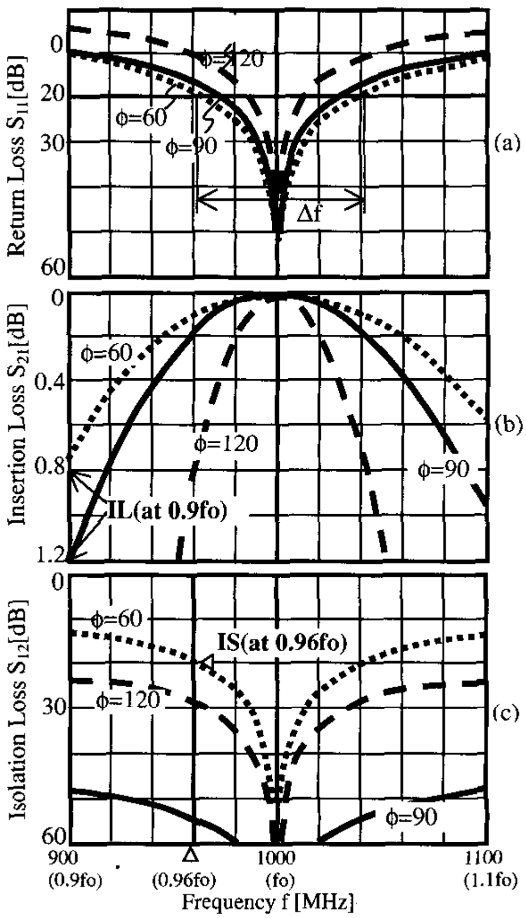

Fig.4 Calculated results of electrical performances of two-port isolator with various cross-angle ϕ.

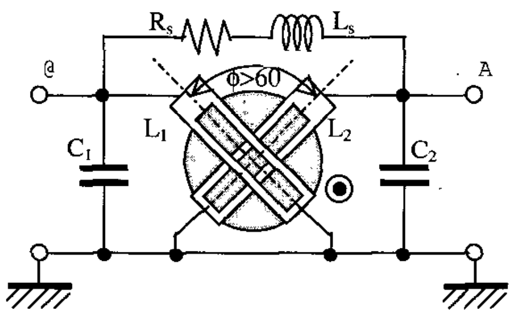

Fig.5 Equivalent circuit for ϕ>90 degree

Fig.6(a) shows the angular dependency of w, IS, IL defined above and normalized magnetic field σ that is necessary for isolator operation[5], over wide range of 40 – 140 degree. The magnetic field σ becomes minimum at ϕ=90 degree and become large at both side of less or more than 90 degree. On the other hand, the bandwidth of return loss, w, becomes maximum and the insertion loss, IL, becomes minimum, at ϕ=60 degree. The region of ϕ>90 degree is not interesting for a practical use due to narrower bandwidth.

Fig.6(b) shows the angular dependency of the design parameters used for calculating Fig.6(a). In the region of ϕ<90 degree, C_w and R=50[Ω] are needed. The connection of L_s and R_s are necessary for ϕ>90 degree. Especially, we found a interesting relation that $C=C_w$ occurs at ϕ=60 degree. The value of L_s becomes maximum at about ϕ=115 degree.

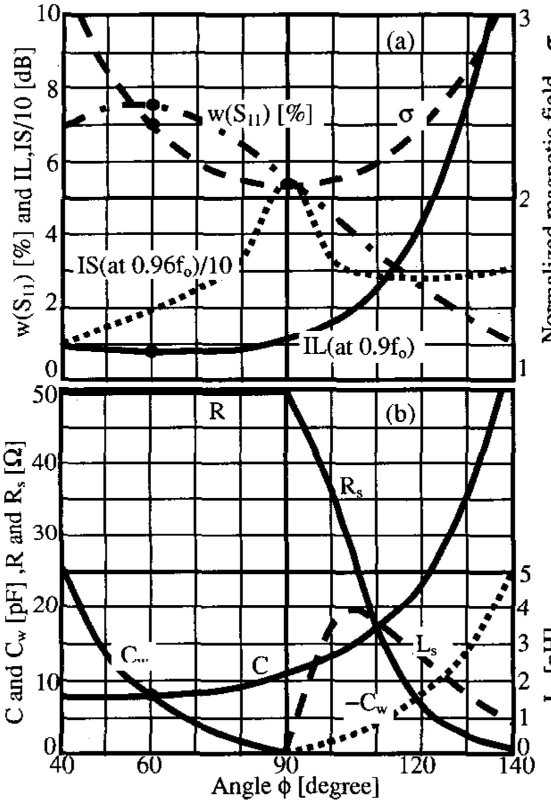

Fig.6 Calculated angular dependency of electric performances and circuit parameters

V. EXPERIMENTAL RESULTS

In order to prove the above theoretical prediction, the experiments were implemented on 360MHz-band relatively larger two-port isolator. Two-piece of garnet disk with 20mmϕx1.5mmt and $4\pi Ms$=900 [G] are used. The experimental result of insertion loss and isolation loss are shown in Fig.7(a)(b). Although it was very difficult to adjust the isolator, we confirmed the largest bandwidth at ϕ=60 degree. It obeys theoretical prediction qualitatively. However, we could not find any clear differences in isolation loss corresponding to each angle ϕ. Furthermore, in order to improve an insertion loss, it was necessary an internal impedance to increase. In this experiment, R=200[Ω] was needed.

We think that these discrepancies between theoretical prediction and experiments are caused by the assumption of perfect symmetrical structure and complete coupling in our theoretical analysis. In order to improve the agreement, the theoretical study on non-symmetrical structure and the experiments on improving coupling will be necessary.

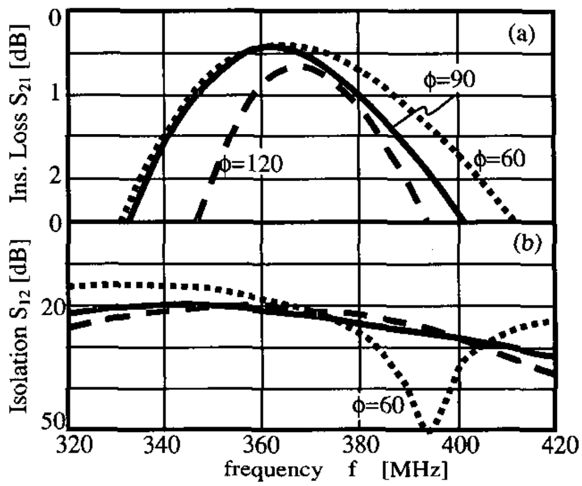

Fig.7 Experimental results of the 360MHz band two-port isolator

VI. CONCLUSIONS

We revealed the angular dependency of two-port isolator using developed circuit simulator. At the angle ϕ=60 degree between two central conductors, the bandwidth of insertion loss becomes maximum. Then the condition is quite similar to the one of a conventional three-port circulator. The theoretical prediction was confirmed qualitatively in 360MHz band experiments.

REFERENCES

1) Hodges et al; US patent 4,016,510 (1977)
2) Dworsky et al; US patent 4,101,850 (1978)
3) Endeby et al; US patent 4,210,886 (1980)
4) T.Okada et al; MTT-S WE4F-4 (2001)
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