Compensation of Equivalent Circuit Model of TE_{011} Mode Cylindrical Cavity Filter

Nam-Young Ryu · Jeong-Hae Lee

Abstract

A proper equivalent circuit model for coupling iris has been derived in order to compensate the length of cavity in a TE_{011} mode cylindrical cavity filter. A method to resolve the difference in bandwidth and feature of ripple systematically has been proposed. This method can be applied to other types of waveguide cavity filter.

Key words : Aperture Theory, Cavity Filter, Equivalent Circuit Model

Ⅰ. Introduction

An iris coupled TE_{011} mode cylindrical cavity filter is often utilized in a high power and low loss microwave system because it has high quality factor[1],[2]. Equivalent circuit model[2] has been frequently used to design this type of filter. However, the frequency response of filter designed with current equivalent circuit model[2] shows much more differences in center frequency, bandwidth, and feature of ripple than expected. These discrepancies are thought to be due to incompleteness of current equivalent circuit model. The frequency dependence of coupling iris results in the center frequency shift since it is not included in current circuit model.

In this paper, we proposed a method to compensate current equivalent circuit model. First, a proper equivalent circuit model for coupling iris has been derived to resolve the center frequency shift and used to compensate the length of cavity. Second, the equations for compensation were obtained by curve fitting of the data simulated by high frequency structure simulator (HFSS)[3] to resolve the differences in bandwidth and feature of ripple.

Ⅱ. Equivalent Circuit Model for Coupling Iris

The structure of a TE_{011} mode cylindrical four-cavity filter is shown in Fig. 1. The radii and heights of four cavities are $R_{1,2,3,4}$ and $h_{1,2,3,4}$, respectively. The lengths of a coupling iris, whose width and height are d and c, respectively, are represented as $t_{1,2,3,4,5}$ in Fig. 1. The input and output ports consist of a rectangular waveguide with a size of $a \times b$.

The frequency response of a filter with current circuit model [2] was simulated using HFSS and the result was illustrated in Fig. 2. As shown in Fig. 2, the frequency response shows much more differences in center frequency, bandwidth, and feature of ripple than expected. It is thought that the difference of the center frequency among these discrepancies is due to the fact that the frequency dependence for coupling iris was not considered in the current circuit model[2]. In this section, a proper equivalent circuit model for coupling iris has been derived to resolve the center frequency shift and used to compensate the length of cavity.

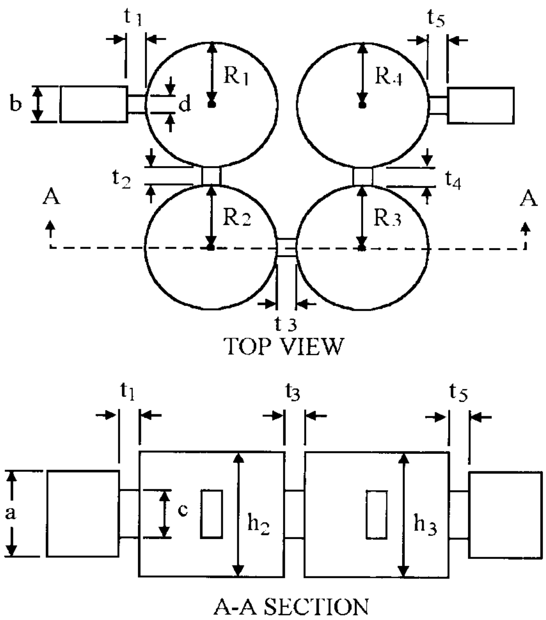

Fig. 1. A structure of TE_{011} mode cylindrical four-cavity filter. ($t_1 = t_5$, $t_2 = t_4$, $R_1 = R_4$, $R_2 = R_3$)

The coupling iris in Fig. 1 can be considered to connect two circular waveguides as shown in Fig. 3. Now that the operational mode inside a cavity is TE_{011} mode, it can be

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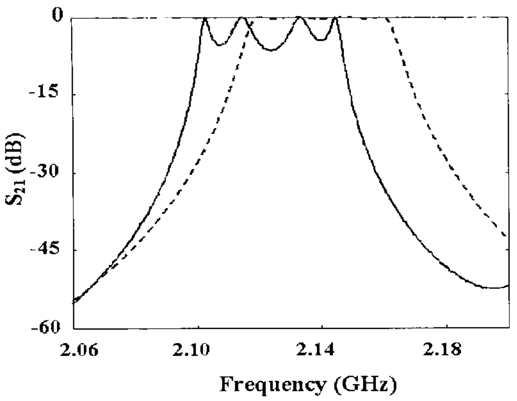

Fig. 2. Comparison of the frequency response of the filter designed using current circuit model with expected response.
······ Expected response (0.5 dB Ripple, Order N=4)
—·· The frequency response of the filter designed using current circuit model

assumed that only TE_{01} mode propagates within the circular waveguide. Since the component of the fields coupled to cavity 2 through iris in Fig. 3 is H_z component, an equivalent circuit for coupling iris can be expressed as shunt inductance (jX) as shown in Fig. 4. Without an iris, the electric and magnetic fields in the waveguide 1 can be represented as (1)-(3).

$$H_z = -j\frac{k_c}{k\eta}A(e^{-j\beta z} + e^{j\beta z})J_0(k_c\rho) \tag{1}$$

$$H_\rho = -\frac{\beta}{k\eta}A(e^{-j\beta z} + e^{j\beta z})J_0'(k_c\rho) \tag{2}$$

$$E_\phi = A(e^{-j\beta z} - e^{j\beta z})J_0'(k_c\rho) \tag{3}$$

Note that k is the wavenumber of the material filling the waveguide region, k_c is the cutoff wavenumber, β is the propagation constant, and η is the wave impedance for the plane wave.

However, the magnetic polarization currents by the iris excite the electric and magnetic fields in the waveguide 1 when the waveguide 2 is connected with an iris. The magnetic polarization currents and amplitude of the excited fields can be derived with Bethe's small aperture theory[2],[4]. The results derived in this paper are represented in (4),(5)

$$\bar{P}_m = -\hat{z}2AM_1J_0(p'_{01})\delta(\rho - R)\delta(\phi)\delta(z) \tag{4}$$

$$A_{01}^{+} = \frac{-1}{P_{01}}\int \bar{h}_{01}\cdot(2j\omega\mu_0\bar{P}_m)dv = \frac{2jAp_{01}'M_1}{\pi R^2\lambda_g} = A_{01}^{-} \quad (5) \tag{5}$$

where p'_{01} is the first root of $J'_0(x)$. The complete fields in

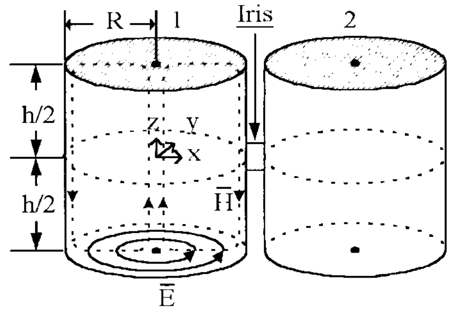

Fig. 3. An iris to connect two circular waveguides.

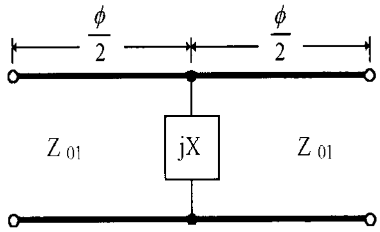

Fig. 4. An equivalent circuit for coupling iris.

the waveguide 1 can now be written as (6) and the reflection coefficient can be found as (7)

$$E_\phi = [(A_{01}^{+} + A)e^{-j\beta z} + (A_{01}^{-} - A)e^{j\beta z}]J_0'(k_c\rho) \tag{6}$$

$$\Gamma = \frac{A_{01}^{-} - A}{A_{01}^{+} + A} \cong \frac{A_{01}^{-} - A}{A} = \frac{2jp_{01}'M_1}{\pi R^2\lambda_g} - 1 \tag{7}$$

Here the denominator of (7) is approximated as A since $A^{+}_{01} \ll A$. Note that A is arbitrary amplitude, M_1 is the magnetic polarizability, and $\bar{h}_{01}$ is the TE_{01} modal fields of a circular waveguide.

The reflection coefficient in Fig. 4 can be found by using circuit analysis to give (8). The comparison of (7) with (8) shows that the iris is equivalent to a normalized inductive reactance as (9). In Fig. 4, ϕ can be derived as (10) from the transmission (ABCD) matrix of the circuit shown in Fig. 4. Therefore, the compensated electrical length of a cavity can be found as (11).

$$\Gamma = -1 + j\frac{2X}{Z_{01}} \tag{8}$$

$$\frac{X}{Z_{01}} = \frac{p_{01}'M_1}{\pi R^2\lambda_g} \tag{9}$$

$$\phi = -\tan^{-1}\frac{2X}{Z_{01}} \tag{10}$$

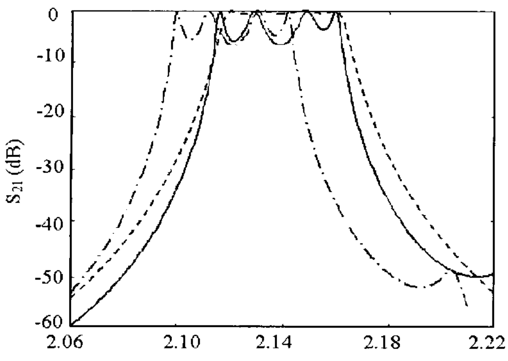

Fig. 5. Frequency responses of the filter with and without compensating the cavity length.
...... Expected response (0.5 dB Ripple, Order N=4)
-·- Without compensation
—— With compensation

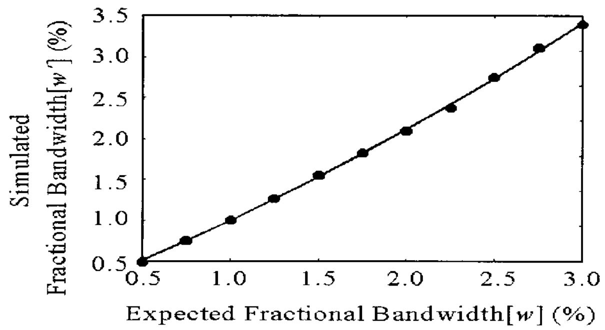

Fig. 6. Fractional bandwidth obtained by simulation with HFSS.

$$\theta_i = \pi - \frac{1}{2}\left[\tan^{-1}\left(\frac{2X_{i-1,i}}{Z_{01}}\right) + \tan^{-1}\left(\frac{2X_{i,i+1}}{Z_{01}}\right)\right] \tag{11}$$

Note that Z_{01} is a wave impedance of TE_{01} mode and θ_i is electrical length of i-th resonator.

Using (11), a filter was designed and simulated with HFSS. Simulation result is illustrated in Fig. 5. When the cavity length of a filter was compensated with (11), its center frequency was approximately equal to the expected value as shown in Fig. 5. However, bandwidth and feature of ripple still show much difference.

Ⅲ. Compensation of Bandwidth and Feature of Ripple

The filters having a fractional bandwidth of 0.5 % to 3.0 % with (11) was designed to resolve the discrepancy in bandwidth. The designed filter was simulated with HFSS. The simulation results are shown in Fig. 6. As a fractional bandwidth increases, the expected fractional bandwidth (w) is not the same as the simulated one (w') because of the limit of circuit model. It is also observed in Fig. 6 that the difference in bandwidth is smaller at small fractional bandwidth as we expected since Bethe's small aperture theory is more accurate at a smaller fractional bandwidth. Equation (12) to compensate bandwidth is obtained by curve fitting of simulated data

$$w' = 9.3040w^2 + 0.8365w + 0.0007 \tag{12}$$

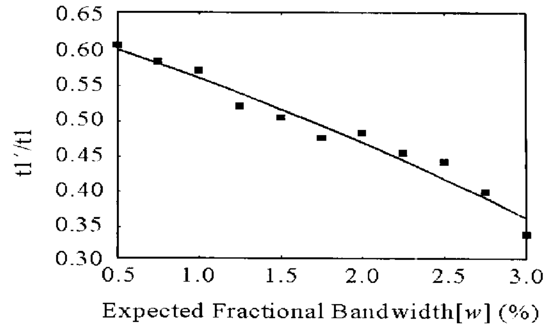

Fig. 7. Ratio of the length of the initial (t_1) and the new iris (t_1').

We gradually varied the length of the first and last iris ($t_1 = t_5$) at the given fractional bandwidth to resolve the difference in feature of ripple. As the length of the first and last iris is varied, feature of ripple is observed being controlled with negligible changes in center frequency and bandwidth. The new iris length (t_1') to produce the expected feature of ripple has been obtained by the above gradual variation of the iris length at different fractional bandwidth from 0.5 % to 3 %. The results are shown in Fig. 7. Equation (13) was obtained to solve the problem of feature of ripple by doing curve fitting for these data.

$$t_1'/t_1 = -75.8599w^2 - 6.9001w + 0.6334 \tag{13}$$

The roots (w) of (12) can be found by substituting the desired fractional bandwidth (w') to (12). If we wish to design the filter having a bandwidth of 2 %, we have to design the filter having slightly narrower bandwidth than 2 %. Then, substituting the initial length (t_1) of the first and last irises to (13), we can find the new length (t_1') of iris. It is also noted that the ratio of t_1'/t_1 is closer to one as the fractional bandwidth is smaller in Fig. 7.

Ⅳ. Results

Table 1. Comparison of sizes of the filter designed with compensated and without compensated circuit model.

Parameters	Without Compensation	With Compensation
a	10.922 cm	10.922 cm
b	5.461 cm	5.461 cm
c	6.000 cm	6.000 cm
d	2.000 cm	2.000 cm
$R_1 = R_4$	10.186 cm	10.186 cm
$R_2 = R_3$	10.186 cm	10.186 cm
$h_1 = h_4$	12.723 cm	12.525 cm
$h_2 = h_3$	12.723 cm	12.595 cm
$t_1 = t_5$	1.6172 cm	0.7042 cm
$t_2 = t_4$	2.0449 cm	2.3886 cm
t_3	2.5917 cm	2.0353 cm

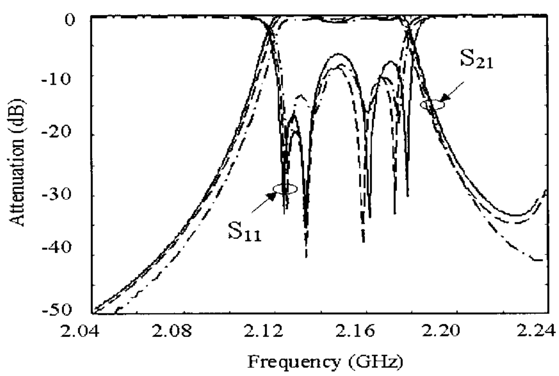

Fig. 8. Comparison of frequency response of the filter.
—— Compensated circuit model in this paper(Simulated with HFSS)
Mode matching method
Measured

Equations (11)-(13) for compensation have been included in the established procedure [2] to design a TE_{011} mode cylindrical cavity filter. We designed the four-cavity filter having a center frequency of 2.148 GHz, a bandwidth of 60 MHz, and a 0.5 dB equal-ripple response. The sizes of the filters designed with compensated and without compensated circuit model are compared in Table 1. The filter designed with compensated circuit model was simulated with HFSS. As illustrated in Fig. 8, the frequency response is compared with measured and computed value with mode matching techniques[5]. The results show good agreement.

To confirm that the above compensation method is valid at other frequency band, the filter was designed at other frequency band. The designed filter has a center frequency of 25 GHz, a bandwidth of 250 MHz, and a 0.5 dB equal-ripple response. The sizes of this filter are shown in Table 2. This result also shows good agreement.

V. Conclusion

Table 2. Size of the filter having center frequency of 25 GHz, bandwidth of 250 MHz, and 0.5 dB ripple.

Parameters	Values
a	0.4800 cm
b	0.2400 cm
c	0.3206 cm
d	0.1069 cm
$R_1 = R_4$	0.5470 cm
$R_2 = R_3$	0.5470 cm
$h_1 = h_4$	0.6760 cm
$h_2 = h_3$	0.6798 cm
$t_1 = t_5$	0.1166 cm
$t_2 = t_4$	0.3108 cm
t_3	0.3455 cm

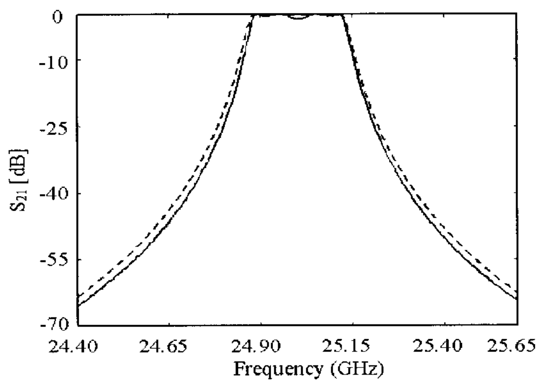

Fig. 9. Frequency response of the filter with the center frequency of 25 GHz.
--- Expected response (0.5 dB Ripple, Order N=4)
—— Simulated result of designed filter with HFSS

A method to compensate current equivalent circuit model of TE_{011} mode cylindrical cavity filter is proposed in this paper. A proper equivalent circuit for coupling iris was derived to compensate the difference of center frequency. The equations for compensation were obtained by curve fitting of the simulated data to resolve the discrepancy of bandwidth and feature of ripple. By comparing the frequency response of filter designed from the method proposed in this paper with that of the filter designed from the mode matching techniques and that of measurement, it has been confirmed that this proposed method is valid. It is expected that the proposed procedure can be applied to other types of waveguide cavity filters.

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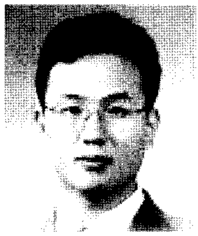

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