

# Design Method for Parallel-Coupled Half-Wavelength Resonator Filter

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**Abstract** Recently, miniaturization of duplexer used in base station is strongly expected. By creating attenuation poles near the passband, out-of-band attenuation becomes steeper. Thus, compact filter with a fewer number of resonators can satisfy a required attenuation specification. The purpose of this study is to establish an analytical design method of attenuation pole for half-wavelength parallel-coupled resonator filters. It was confirmed by circuit simulation how attenuation pole frequencies moved by respective capacitances connected to coupled-resonators. Three attenuation poles were generated and the frequencies were controlled, successfully. Circuit equation of the filter was derived and attenuation pole frequencies were designed analytically. In addition, to design the passband characteristics, design chart is created.

**Keyword** Filter with Attenuation Pole, Half-Wavelength, Parallel-Coupled, Attenuation Frequency, Base-Station

## 1. INTRODUCTION

Recently, data traffic through smart phone is increasing rapidly. Thus, additional installation of base station is required. But, volume of duplexer occupies about half of a small base station. Usually, 10- to 15-pole filters are used for transmitting and receiving, respectively. Thus, miniaturization of filter is very important. One approach is to reduce the number of resonators. Although filter gets higher attenuation by increasing number of resonators, it also can be attained by creating attenuation poles near the passband [1]-[3].

A resonator consists of an inductor and a capacitor and those values are calculated by conventional filter theory. In microwave band, the resonator is converted to a distributed circuit resonator. But, it is difficult to design attenuation poles created by anti-resonance of electromagnetic coupling between resonators. The objective of this study is to establish a design method for attenuation pole of a half-wavelength parallel-coupled resonator filter.

A filter with attenuation poles might be designed either by a strict method using a characteristic function or by a simple way based on Chebyshev characteristic with additional attenuation pole [4]. In this study, the simple way is adopted.

So far, there is few report on design for half-wavelength coupled-resonator filter, in contrast to quarter-wavelength resonator filter [5]. Dependency of three attenuation pole frequencies on connected capacitances is studied by simulation. Then, circuit equation of the filter is derived and analytical design method of attenuation pole frequency is investigated. In addition, to design the passband characteristics, design chart is created. Finally, the attenuation pole frequencies are checked by an experimental filter, which is designed based on this technique.

## 2. CIRCUIT SIMULATION

Transfer characteristics of coupled-resonator with resonant frequency of 2GHz are indicated in Fig.1. Quarter-wavelength coupled-line has an attenuation pole at 2GHz. On the other hand, half-wavelength coupled-line has three attenuation poles, at 1GHz, 2GHz and 3GHz. Half-wavelength coupled-resonator can make much more attenuation poles than quarter-wavelength resonator. Thus, attenuation performance of half-wavelength filter becomes steeper. Passband could be shifted from attenuation pole frequency by loaded capacitance, in the same manner with quarter-wavelength comb-line filter. Passband characteristic can be controlled by coupling coefficient, electrical length of coupled-line and loaded capacitor. It will be discussed later.

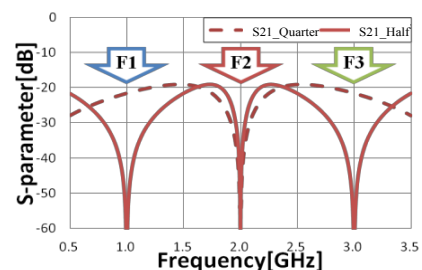


Fig.1. Transfer characteristics of 2GHz coupled-resonator

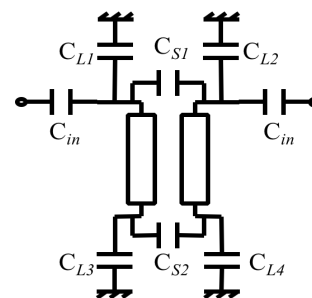


Fig.2. Circuit configuration of coupled-resonator filter

A circuit shown in Fig.2 is analyzed by circuit simulator. Coupling coefficient of coupled-line is expressed by the following equation,

$$C = \frac{Z_e - Z_o}{Z_e + Z_o} \quad (1).$$

This parameter is used for design of passband width, later.

Here, capacitances are set as  $C_{L1}=C_{L2}$ ,  $C_{L3}=C_{L4}$ , and dependencies on capacitances are examined.  $C_{in}$  is input/output capacitor for matching. It is ignored in the first step, because only attenuation pole frequency is considered. First, each connected capacitance is changed separately, and variations of attenuation pole frequencies are checked.

Figure 3 shows variations of attenuation pole frequencies for changing  $C_{S1}$ . If  $C_{S1}$  increases, only  $F_2$  moves to lower frequency, while frequencies  $F_1$  and  $F_3$  does not change. Figure 4 shows variations of attenuation pole frequencies for changing  $C_{L1}$ . Even  $C_{L1}$  increases, pole frequencies don't change. Thus,  $C_{L1}$  can be used for passband frequency adjustment. Figure 5 shows variations of attenuation pole frequency for changing  $C_{S2}$ . If  $C_{S2}$  increases, all frequencies change.  $F_1$  moves to higher frequency and  $F_2$  moves to lower frequency. At  $C_{S2}$  of 0.31pF,  $F_1$  and  $F_2$  are combined at 1.4GHz.  $F_3$  moves to higher frequency, and frequency becomes highest at 0.13pF. Then,  $F_3$  moves to lower frequency. Figure 6 shows variations of attenuation pole frequency for changing  $C_{L3}$ . If  $C_{L3}$  increases,  $F_1$  and  $F_3$  move to lower frequencies, while  $F_2$  does not change.

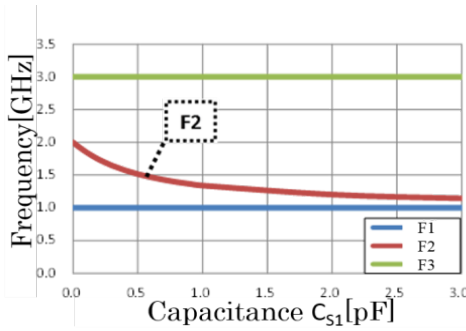


Fig.3.Frequency chart for  $C_{S1}$

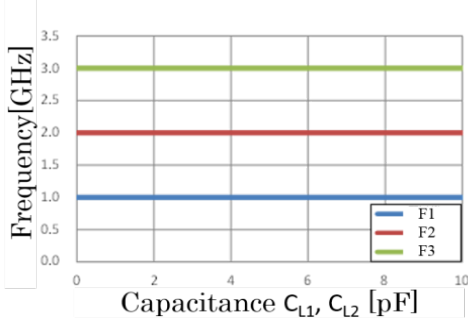


Fig.4. Frequency chart for  $C_{L1}$

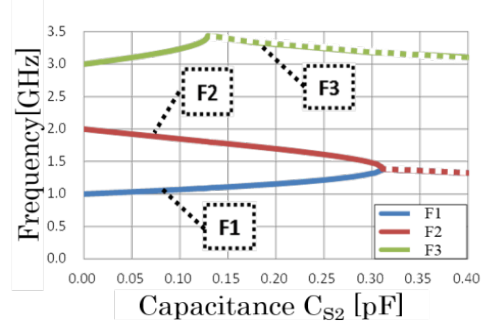


Fig.5.Frequency chart for  $C_{S2}$

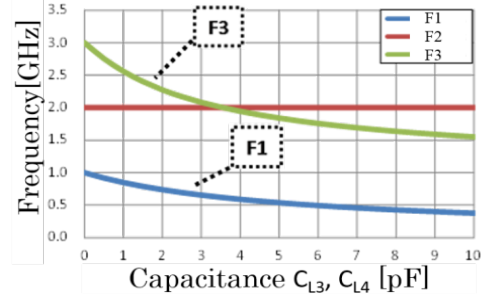


Fig.6.Frequency chart for  $C_{L3}$

### 3. ANALYSIS USING CIRCUIT EQUATION

Circuit equations are formulated for respective connected capacitors [6]. Eq. (2) is for capacitor  $C_{S1}$ .

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = j \frac{1}{2(1-2\omega C_{S1}x_1x_2)} \begin{bmatrix} x_1+x_2-2\omega C_{S1}x_1x_2 & x_1-x_2-2\omega C_{S1}x_1x_2 \\ x_1-x_2-2\omega C_{S1}x_1x_2 & x_1+x_2-2\omega C_{S1}x_1x_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (2)$$

Here,  $x_1$  and  $x_2$  are  $jx_1=z_{11}+z_{12}$  and  $jx_2=z_{11}-z_{12}$  and functions of frequency. Attenuation pole frequency is calculated from  $Z_{21}=0$  as shown in (3).

$$\omega_p = \frac{x_1 - x_2}{2C_{S1}x_1x_2} \quad (3)$$

An equation for capacitor  $C_{L1}$  is shown in (4). Attenuation pole frequency is given by  $Z_{12}=x_1-x_2=0$ , and it depends on neither  $C_{L1}$  nor  $C_{L2}$ .

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = j \frac{1}{2(1-\omega C_{L1}x_1)(1-\omega C_{L1}x_2)} \begin{bmatrix} x_1+x_2-2\omega C_{L1}x_1x_2 & x_1-x_2 \\ x_1-x_2 & x_1+x_2-2\omega C_{L1}x_1x_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (4)$$

An equation for capacitor  $C_{S2}$  is shown in (5). Here,  $x_3$  and  $x_4$  are  $jx_3=z_{13}+z_{14}$  and  $jx_4=z_{13}-z_{14}$ . And,  $z_{11}$ ,  $z_{12}$ ,  $z_{13}$  and  $z_{14}$  are also functions of frequency.

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} - \frac{(z_{13}-z_{14})^2}{2(z_{11}-z_{12})+1/j\omega C_{S2}} & z_{12} + \frac{(z_{13}-z_{14})^2}{2(z_{11}-z_{12})+1/j\omega C_{S2}} \\ z_{12} + \frac{(z_{13}-z_{14})^2}{2(z_{11}-z_{12})+1/j\omega C_{S2}} & z_{11} - \frac{(z_{13}-z_{14})^2}{2(z_{11}-z_{12})+1/j\omega C_{S2}} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (5)$$

Attenuation pole frequency is given by  $Z_{21}=0$ .

$$\omega_p = \frac{z_{12}}{C_{S2} \left\{ (z_{13}-z_{14})^2 + 2z_{12}(z_{11}-z_{12}) \right\}} \quad (6)$$

An equation for capacitor  $C_{L3}$  is shown in (7).

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = j \frac{1}{2(1 - \omega C_{L3} x_1)(1 - \omega C_{L3} x_2)} \begin{bmatrix} A' & B' \\ B' & A' \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$A' = x_1 + x_2 + \omega^2 C_{L3}^2 \{x_2(x_1^2 - x_1^2) + x_1(x_2^2 - x_2^2)\} - 2\omega C_{L3} x_1 x_2 - \omega C_{L3} \{x_1^2 - x_1^2 + (x_2^2 - x_2^2)\}$$

$$B' = x_1 - x_2 + \omega^2 C_{L3}^2 \{x_2(x_1^2 - x_1^2) - x_1(x_2^2 - x_2^2)\} - \omega C_{L3} \{x_1^2 - x_1^2 - (x_2^2 - x_2^2)\}$$
(7)

Attenuation pole frequencies are given by  $Z_{2l} = 0$ . A cubic equation was obtained. It is not shown here, because it is very complicated.

In the next step, circuit equation for connecting all capacitors is considered.

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = j \begin{bmatrix} \frac{X_1 + X_2 - 2\omega(C_{S1} + C_{L1})X_1 X_2}{2[1 - \omega C_{L1} X_1][1 - \omega(2C_{S1} + C_{L1})X_2]} - \frac{1}{\omega C_m} & \frac{X_1 - X_2 - 2\omega C_{S1} X_1 X_2}{2[1 - \omega C_{L1} X_1][1 - \omega(2C_{S1} + C_{L1})X_2]} \\ \frac{X_1 - X_2 - 2\omega C_{S1} X_1 X_2}{2[1 - \omega C_{L1} X_1][1 - \omega(2C_{S1} + C_{L1})X_2]} & \frac{X_1 + X_2 - 2\omega(C_{S1} + C_{L1})X_1 X_2}{2[1 - \omega C_{L1} X_1][1 - \omega(2C_{S1} + C_{L1})X_2]} - \frac{1}{\omega C_m} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$jX_1 = A' + B' \quad jX_2 = A' - B'$$

$$A' = j \frac{(x_1 + x_2)(1 - \omega C_{L3} x_1)(1 - \omega(2C_{S2} + C_{L3})x_2) + \omega C_{L3}(1 - \omega(2C_{S2} + C_{L3})x_2)x_1^2 + \omega(2C_{S2} + C_{L3})(1 - \omega C_{L3} x_1)x_2^2}{2(1 - \omega C_{L3} x_1)(1 - \omega(2C_{S2} + C_{L3})x_2)}$$

$$B' = j \frac{(x_1 - x_2)(1 - \omega C_{L3} x_1)(1 - \omega(2C_{S2} + C_{L3})x_2) + \omega C_{L3}(1 - \omega(2C_{S2} + C_{L3})x_2)x_1^2 - \omega(2C_{S2} + C_{L3})(1 - \omega C_{L3} x_1)x_2^2}{2(1 - \omega C_{L3} x_1)(1 - \omega(2C_{S2} + C_{L3})x_2)}$$
(8)

Validity of circuit equation was confirmed by comparing the performances calculated by the equation and obtained by circuit simulation. The results are shown in Fig. 7. The both are coincided. Thus, it is confirmed that the equation is correct.

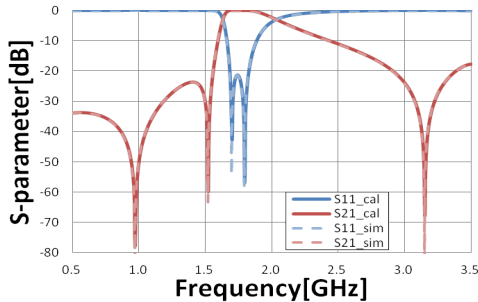


Fig.7. Performances calculated by equation and by circuit simulation

#### 4. FILTER DESIGN

An analytical design method of attenuation pole frequency was established. But, passband design is still not. In the preceding investigation, coupling and electrical length of coupled-lines are fixed. These parameters could be used for design of a desired passband characteristic. Final objective of this work is to establish a simultaneous analytical design for both attenuation pole frequency and passband characteristic. However, it is not easy at this moment. Thus, design charts for passband characteristic are considered. Figures 8 and 9 show the design charts for tuning the passband characteristics. Figure 8 illustrates performance variations for different couplings between coupled-lines. The passband bandwidth can be controlled by the coupling. Figure 9 illustrates performance variations for different electrical lengths of the lines. The center frequency

of passband can be controlled by the electrical length. Along with capacitance values, attenuation pole frequencies and passband characteristic can be designed simultaneously to meet with a desired filter specification.

To demonstrate performance of half-wavelength parallel-coupled resonator filter,  $C_{L1}$ ,  $C_{L2}$  and  $C_{in}$  were tuned manually and these design charts were used for tuning passband characteristics. Passband frequency is set to 2GHz and attenuation pole frequencies are set to 0.9GHz, 1.75GHz and 3.15GHz, respectively. Figure 10 shows the simulated performance of the half-wavelength parallel-coupled resonator filter. Very excellent filter performance was obtained as shown in the figure. The circuit parameters are shown in Table I.

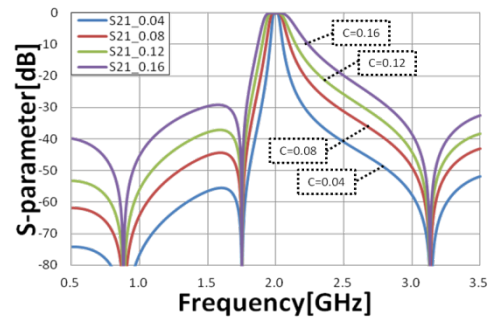


Fig.8. Passband width chart for coupling coefficient

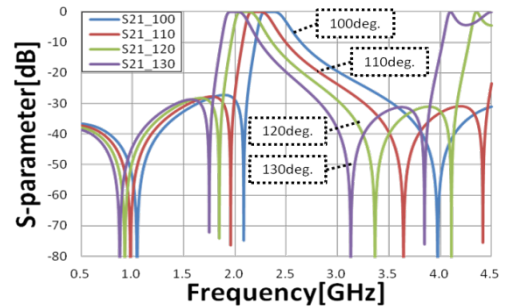


Fig.9. Passband frequency chart for electrical length

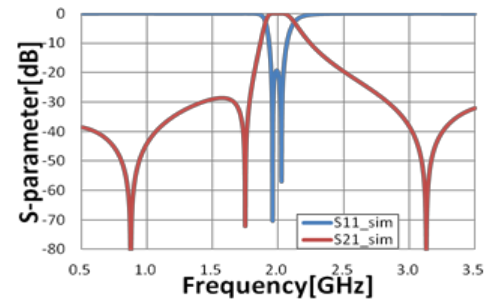


Fig.10. Performance of half-wavelength parallel-coupled resonator filter

Table I. Circuit parameters of half-wavelength parallel-coupled resonator filter

$C_{S1}$	2.7pF	$C_m$	2.8pF
$C_{S2}$	0pF	$Z_e$	6.5Ω
$C_{L1}$	0.3pF	$Z_o$	5Ω
$C_{L3}$	10.3pF	$\theta(@2GHz)$	130deg.

**5. EXPERIMENTAL FILTER**

An experimental two-pole filter using micro strip-line resonator was designed and fabricated. Design parameters were passband frequency of 2.1GHz, bandwidth of 150MHz, and attenuation pole frequencies of 1.3GHz, 3.1GHz and 4.1GHz, respectively. Figure 11 is a photograph of the fabricated filter. The filter size excluding connector is 6.8mm by 28mm by 1mm.

The filter performance is shown in Fig. 12. The insertion loss was less than 1.0dB and the return loss was more than 10dB. Attenuation pole frequencies were created at 1.26GHz, 3.06GHz and 4.06GHz, respectively. They are very close to the designed values. The return loss was a little bit worse than the designed value, because chip capacitors with standard accuracy were used for input/output coupling. It could be improved by using high-accuracy capacitors.

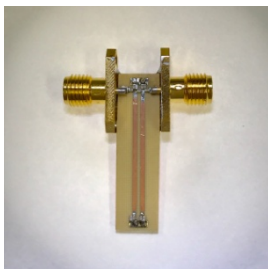


Fig.11. Photograph of experimental filter

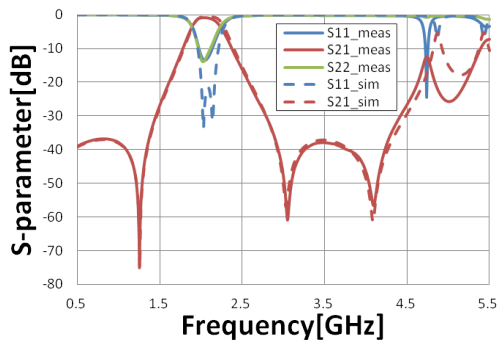


Fig.12. Performance of experimental filter

Table II. Circuit parameter of experimental filter

$C_{S1}$	0.2pF	$C_m$	1.5pF
$C_{S2}$	0pF	$Z_e$	76.4Ω
$C_{L1}$	1.2pF	$Z_o$	57.9Ω
$C_{L3}$	0.6pF	$\theta (@2.1GHz)$	88.5deg.

**6. CONCLUSION**

By using half-wavelength parallel-coupled resonator, three attenuation poles are created with 2-pole filter. It was confirmed by simulation that the attenuation pole frequencies were controlled by values of connected capacitances. The transfer function was derived from circuit equation. As a result, three attenuation pole frequencies could be

calculated as solutions of a cubic equation. It was confirmed that the filter performance with the prescribed attenuation pole frequencies could be achieved by tuning the values of connected capacitances. To design the passband characteristic, design charts for coupling and electrical length of the coupled-lines were illustrated. An experimental filter using micro strip-line resonator was designed and fabricated. It showed an excellent performance with designed attenuation pole frequencies.

This time, only two-pole filter was investigated. But, the authors expect a possibility that much more number of attenuation pole can be created by half-wavelength filter, if the number of resonator is increased.

The remaining subject is to establish a simultaneous analytical design method of both passband characteristic and attenuation pole frequencies by using circuit equation. It will be achieved in the next step.

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