A Study on Input/Output Coupling Methods of Constant Absolute Bandwidth Tunable Filters

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Abstract In recent years, with the increased demand for communication traffic, wireless communication has been performed in various frequency bands, and tunable filters that correspond to different frequency bands have attracted attention. However, the conventional tunable filter has a problem because the bandwidth changes significantly when the center frequency changes. This research investigates input/output coupling methods of a tunable filter with constant absolute bandwidth designed based on the circuit theory. The various input/output structures were compared.

Keyword Tunable filter, Constant absolute bandwidth, I/O coupling, Electromagnetic coupling

1. Introduction

With increased communication traffic, wireless communication has recently been performed in various frequency bands. Fifth-generation mobile communications (5G) and next-generation standards will be promoted, accelerating the expansion of frequency bands [1], [2]. Thus, current smartphones are becoming multi-band compatible. However, increasing the number of mounted filters is a big problem. Filter size should be reduced.

One approach to filter miniaturization is the tunable bandpass filter. Usually, for filters used in base stations and terminals, it is necessary to prepare one filter for one frequency. On the other hand, a tunable filter can switch between multiple frequencies in a single BPF automatically or manually by electrical or mechanical means, leading to smaller filters. Fig.1 shows the circuit diagram of the tunable BPF.

However, conventional tunable BPFs have technical problems, such as increased loss and change in bandwidth when the center frequency is changed. In particular, the bandwidth fluctuation causes various issues, such as interference with other radio waves. Fig.2 shows the typical performance of a conventional tunable BPF.

To avoid this problem, it is necessary to control the coupling coefficient and the external Q value according to changes in the center frequency. In recent research, to keep the absolute bandwidth constant, a method of changing the electric field distribution on the resonator according to the resonance frequency is used, and such a tunable BPF with a constant bandwidth has been proposed [3], [4]. However, since the coupling coefficient and the external Q value are controlled by adjusting the line-to-line distance and coupling position, the design is complicated because it can only be designed by electromagnetic field simulation. Moreover, when design parameters such as frequency and substrate are changed, it is necessary to redesign an optimal structure by electromagnetic field simulation, which may cost a lot.

In the preceding research, we proposed a new design method based on the circuit theory of tunable BPF and verified the effectiveness of the method by showing a design example based on the proposed approach [5], [6]. This paper investigates input/output coupling methods of the tunable filter with constant absolute bandwidth.

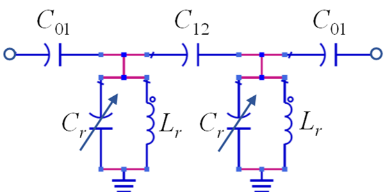

Fig.1 Equivalent circuit of tunable BPF

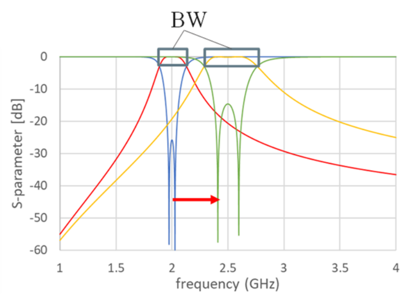

Fig.2 Typical characteristics of conventional tunable BPF

2. Design Theory of Proposed Tunable Filter

In the proposed design method, the ideal curve of the susceptance variation of the coupling element is calculated based on the filter design theory. Then, it is approximated by the susceptance curve of the LC parallel circuit. By solving the simultaneous equations (1) at the two frequencies of the upper limit frequency and the lower limit frequency of the target band, the L value and the C value are calculated so that the susceptances of the two match. The input/output coupling is also designed in the same procedure.

$$\begin{cases} B(f_1) = 2\pi f_1 C_{12} - \dfrac{1}{2\pi f_1 L_{12}} \\ B(f_2) = 2\pi f_2 C_{12} - \dfrac{1}{2\pi f_2 L_{12}} \end{cases} \qquad (1)$$

Fig.3 shows the basic circuit configuration of the proposed tunable bandpass filter. The element values of L and C in the coupling structures were calculated by equations (2) and (3) based on (1).

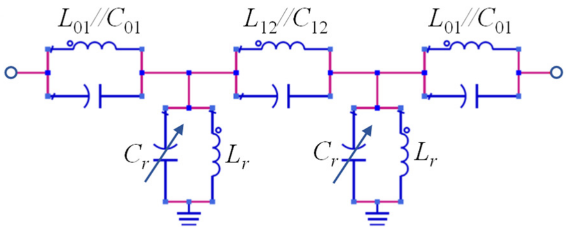

Fig.3 Proposed tunable BPF circuit

$$C = \frac{\dfrac{B_1}{\omega_2} - \dfrac{B_2}{\omega_1}}{\dfrac{\omega_1}{\omega_2} - \dfrac{\omega_2}{\omega_1}} \qquad (2)$$

$$L = \frac{\left(\dfrac{\omega_1}{\omega_2} - \dfrac{\omega_2}{\omega_1}\right)}{\omega_2 B_1 - \omega_1 B_2} \qquad (3)$$

In this way, a constant absolute bandwidth characteristic can be achieved. The design example below is for a resonator inductance L_{ri} of 2 nH, a ripple of 0.05 dB, a bandwidth of 100 MHz, and a center frequency of 2 GHz to 2.5 GHz. Fig.4 and 5 show ideal inter-resonator coupling susceptance curves and ideal input/output susceptance curves. From the calculation results, the susceptance is negative at the design frequency, so the filter should be inductively coupled. The obtained element values and the parameters of the resonator and tuning capacitor are listed in Table I. C_{tune} indicates a tuning capacitor to vary the center frequency. Fig.6 shows the simulation performance of the designed tunable filter. The responses of 2.0 GHz, 2.25 GHz, and 2.5 GHz are drawn in an overlay. As expected, it exhibits constant absolute bandwidth characteristics.

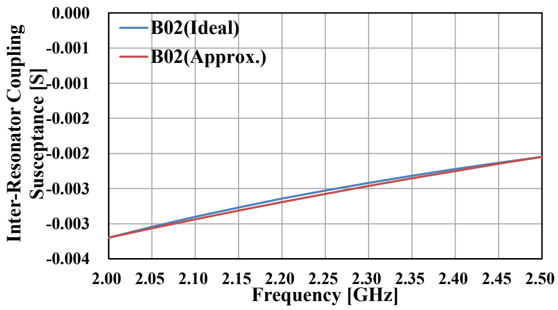

Fig.4 Ideal and calculated interstage susceptance curves

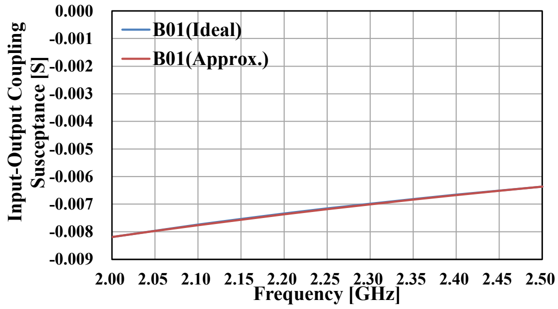

Fig.5 Ideal and calculated I/O susceptance curves

TABLE I. Element values of I/O and interstage, and parameters of the resonator and tuning capacitor

	L_{01}, L_{12}	C_{01}, C_{12}
I/O coupling	9.239nH	0.0335pF
Interstage coupling	18.35nH	0.0905pF

	L_r	C_r	C_{tune}
2.00GHz	2.0nH	2.5247pF	1.4545pF
2.25GHz	2.0nH	2.5247pF	0.6047pF
2.50GHz	2.0nH	2.5247pF	0.0000pF

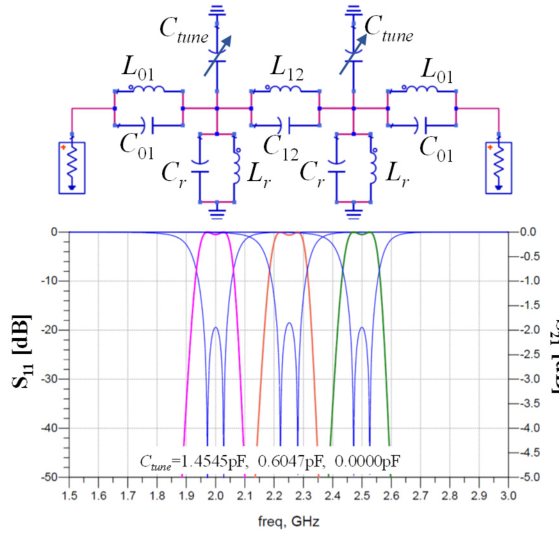

Fig.6 Simulation of the designed tunable filter

3. Design Example of GHz Band Tunable Filter

Using only distributed circuit elements is desirable to realize a GHz-band tunable filter. Therefore, in this research, we design tunable filters by applying the design theory of electromagnetically coupled quarter-wavelength transmission lines [6].

The electromagnetic coupling of coupled lines can be expressed by a parallel resonance circuit of LC [7]. Fig.7 shows the structure and the equivalent circuit.

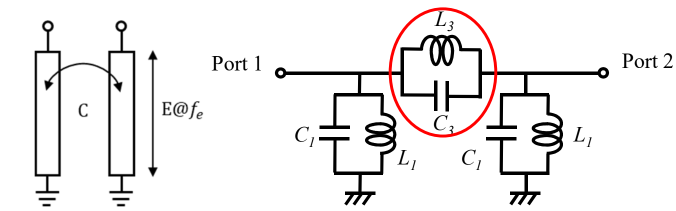

Fig.7 Electromagnetic coupling line and equivalent circuit

Based on the circuit theory of coupled lines, the inductor L_1 and capacitor C_1 are derived from the even-mode impedance, and the coupling inductor L_3 and capacitor C_3 are derived from the even- and the odd-mode impedances. The obtained values are an even-mode impedance of 30.58 Ω, an odd-mode impedance of 25.11 Ω, and an electrical length of 54.067 degrees at 2.25 GHz. The equivalent circuit parameters of the coupled lines are listed in Table II.

TABLE II. Equivalent circuit parameters of coupled-lines

	C_1	L_1	C_3	L_3
Coupled lines	0.828pF	2.00nH	0.0902pF	18.37nH
Target value	2.525pF	2.00nH	0.0905pF	18.35nH

Because the even-mode impedance was determined so that the inductance coincides with the inductor L_1, the capacitance missing from the resonator was added as loaded capacitance C_L. The circuit parameters for the coupled-line-type filter are listed in Table III. A simulation of the filter characteristics was performed using these design values. The results are shown in Fig.8. The designed tunable filter showed a constant bandwidth.

TABLE III. Circuit parameters for coupled-line-type filter

Input and Output Coupling	L_{01}	C_{01}
	9.239nH	0.0335pF

Coupled transmission line	Z_{even}	Z_{odd}	Electrical length @2.25GHz
	30.58Ω	25.11Ω	54.067deg.

	C_L	C_{tune}
2.00GHz	1.6966pF	1.4545pF
2.25GHz	1.6966pF	0.6047pF
2.50GHz	1.6966pF	0.0000pF

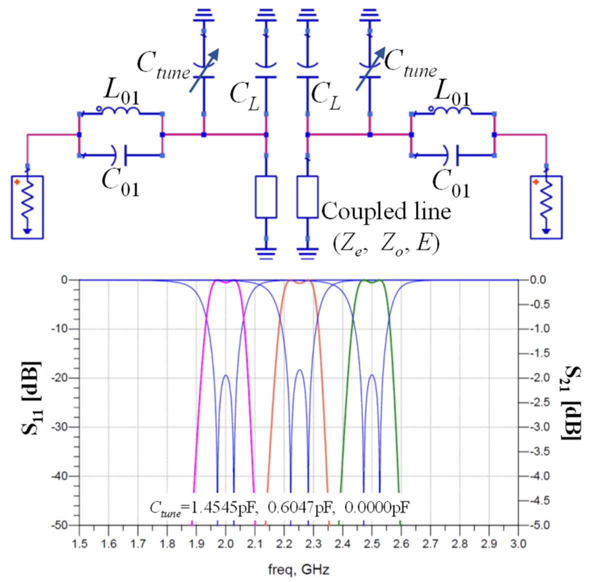

Fig.8 Simulation of an EM-coupled tunable filter

4. Investigation of Input/Output Structure

A. Series-resonator-type I/O structure

Since the inductance is challenging to realize when creating the elements of the input/output circuit, we investigated the input/output structures to improve it.

First, we investigated the series-resonator-type input/output structure. The equivalent circuit is shown in Fig.9, and the L and C are calculated by equations (4) and (5).

$$C = \frac{B_1 B_2 \left(\frac{\omega_2}{\omega_1} - \frac{\omega_1}{\omega_2} \right)}{\omega_1 B_1 - \omega_2 B_2} \tag{4}$$

$$L = \frac{\frac{1}{\omega_2 B_1} - \frac{1}{\omega_1 B_2}}{\frac{\omega_2}{\omega_1} - \frac{\omega_1}{\omega_2}} \tag{5}$$

The element values of L and C in the series input/output structure obtained from equations (4) and (5) are L of 10.516 nH and C of 7.886 pF. The circuit parameters for series-resonator-type I/O structures are listed in Table IV. Fig. 9 shows the results of the simulation. As shown in Fig.9, a constant bandwidth characteristic was obtained. However, the element values of the inductor and the capacitor become larger than those of the parallel-resonator-type shown in Table I. Thus, it seems there is no merit in adopting a series-resonator-type input/output structure.

TABLE IV. Circuit parameters for series-resonator-type I/O structures

Input and Output Coupling	L_{01}	C_{01}
	10.516nH	7.8863pF
Inter-resonator Coupling	L_{12}	C_{12}
	18.35nH	0.0905pF

	L_r	C_r	C_{tune}
2.00GHz	2.0nH	2.5247pF	1.4545pF
2.25GHz	2.0nH	2.5247pF	0.6047pF
2.50GHz	2.0nH	2.5247pF	0.0000pF

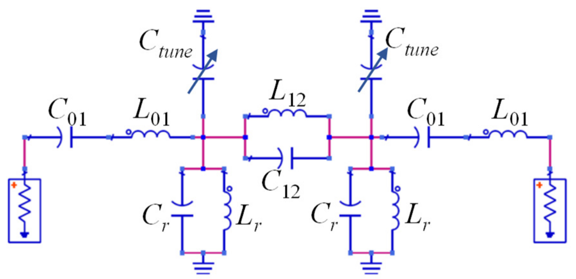

Fig.9 Simulation with series-resonator-type I/O (continued)

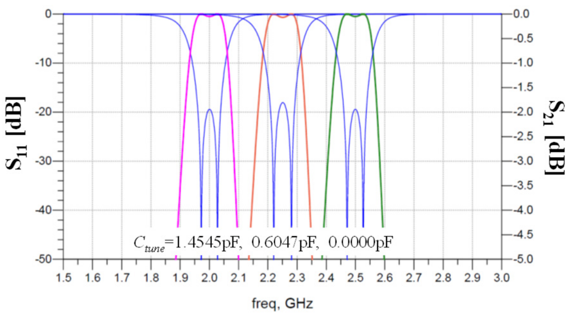

Fig.9 Simulation with series-resonator-type I/O

B. Lowpass-filter-type I/O structure

Secondly, we investigated the lowpass-filter-type input/output structure. The circuit parameters for lowpass-filter-type I/O structures are listed in Table V. The equivalent circuit is shown in Fig.10. The element values of *L* and *C* for the LPF type input/output structure were obtained as *L* of 10.43 nH and *C* of 0.5 pF. Since the equations for deriving these values are very complex, they were obtained by tuning method in simulation this time.

TABLE V. Circuit parameters for lowpass-filter-type I/O structures

Input and Output Coupling	L_{01}	C_{01}
	10.43nH	0.5pF
Inter-resonator Coupling	L_{12}	C_{12}
	18.35nH	0.0905pF

	L_r	C_r	C_{tune}
2.00GHz	2.0nH	2.5247pF	1.4545pF
2.25GHz	2.0nH	2.5247pF	0.6047pF
2.50GHz	2.0nH	2.5247pF	0.0000pF

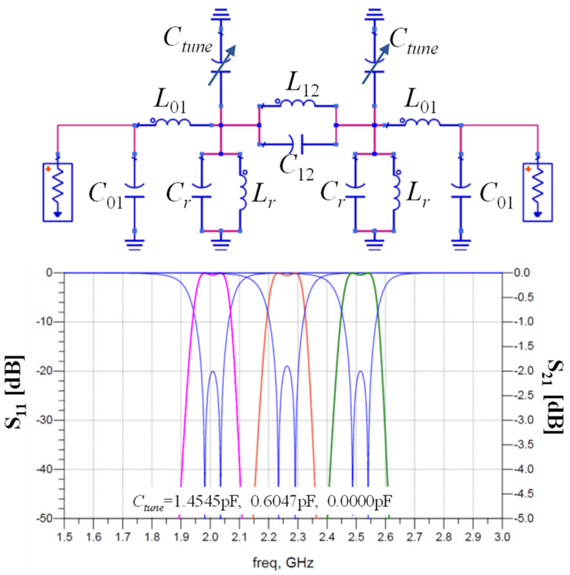

Fig.10 Simulation with LPF-type I/O

A simulation was performed again based on the above parameters. The results are shown in Fig.10. As shown in Fig.10, the designed tunable filter also showed a constant bandwidth.

C. Replacing inductor with transmission line

Comparing the results of the parallel-resonator-type, the series-resonator-type, and the lowpass-filter-type I/O structures, obtained constant bandwidth characteristics are almost the same. The required inductance value was the smallest for the parallel-resonator-type I/O structure. Thus, we adopted the parallel-resonator-type to construct a filter circuit that does not use an inductor. We replaced the inductor of the I/O structure of the parallel-resonator-type with a transmission line and performed the simulation. The circuit parameters for the filter replacing the inductor with a line are listed in Table VI. Since the characteristics of the inductor and the transmission line are slightly different, the values of C_{01} and C_L have to be slightly modified. The results are shown in Fig.11. The characteristic impedance of the transmission line was 300 Ω , with the electrical length 25.2 degrees. The values of C_{01} and C_L are set to 0.05pF and 1.65pF, respectively. The characteristic impedance of the line was too high to fabricate the line. So, it still needs some improvement for the input/output structure. It is a future task.

TABLE VI. Circuit parameters for the filter replacing inductor with a line

Input and Output Coupling	C_{01}	TL_{01}	
		Z_0	Electrical length @2.25GHz
	0.05pF	300Ω	25.2deg.

Coupled transmission line	Z_{even}	Z_{odd}	Electrical length @2.25GHz
	30.58Ω	25.11Ω	54.067deg.

	C_L	C_{tune}
2.00GHz	1.65pF	1.4545pF
2.25GHz	1.65pF	0.6047pF
2.50GHz	1.65pF	0.0000pF

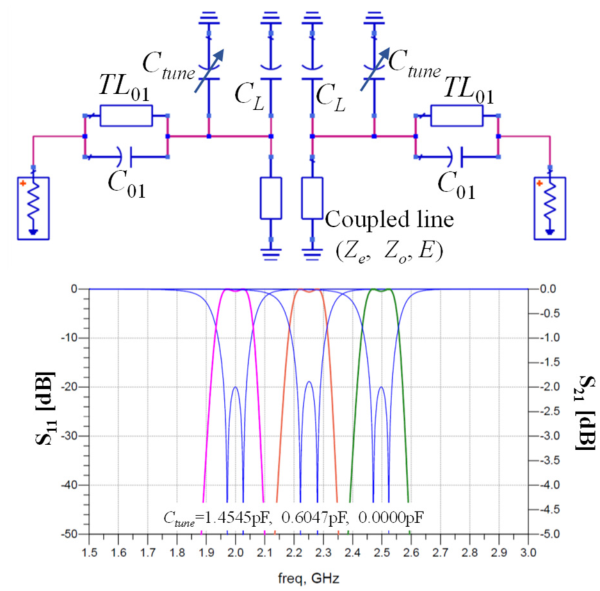

Fig.11 Simulation for filter replacing inductor with a line

5. Conclusion

Based on circuit theory, we proposed a new design method for tunable filters with constant absolute bandwidth. As a design example, it was confirmed by simulation that it is possible to design while keeping the bandwidth constant at the center frequency of 2.0GHz to 2.5GHz.

To fabricate a GHz-band tunable filter, it is desirable to realize the filter using only distributed circuit elements. The inter-resonator coupling was achieved by electromagnetically coupled quarter-wavelength transmission lines. Thus, the inductor is not required for the inter-resonator coupling.

The parallel-resonator-type, the series-resonator-type, and the lowpass-filter-type input/output structures were compared. The constant bandwidth characteristics were obtained for all structures. The inductance value of the parallel-resonator-type was the smallest. Thus, the inductor of the parallel-resonator-type was replaced with a transmission line.

Although a constant absolute bandwidth performance was obtained, the required characteristic impedance was too high to fabricate the line. It is a future task to improve the input/output structure.

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