

# Design of an Active Tunable Bandpass Filter for Spectrum Sensing Application in the TVWS Band

Dong-Su Kim · Do-Hyun Kim · Sang-Won Yun\*

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## Abstract

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In this paper, we propose an active tunable bandpass filter (BPF) for efficient spectrum sensing in the TV White Space (TVWS) band. By designing a narrow bandwidth, it is possible to improve the sensing probability. The basic circuit configuration involves switching the PIN diode compromising capacitor bank to change the capacitance of the LC resonant circuit. To cover the whole TVWS band effectively, we add a varactor diode, and the bandwidth is set to 25-MHz. We improve the insertion loss by using the active capacitance circuit. The tunable BPF in the TVWS band with a 20-MHz interval is designed to have 11 channels with a bandwidth of 25 MHz and a low insertion loss of 1.7–2.0 dB.

**Key Words:** Active Filter, Negative Resistance, Tunable Bandpass Filter (BPF), TV White Space.

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## I. INTRODUCTION

Recently, broad frequency bandwidth has become in demand as data traffic has increased owing to a large number of multi-media data transmissions. However, as the available frequency bandwidth is limited, the securing of a new bandwidth or the identification of new ways of using existing bandwidth efficiently is needed. When sharing TV White Space (TVWS), in the case of the latter, spectrum sensing should be done to determine the unoccupied frequency bandwidth, avoiding primary users. The research regarding this problem has been actively ongoing and many methods of spectrum sensing were proposed [1]. In order to acquire a high tuning speed as well as the accuracy, we propose a narrowband tunable bandpass filter, which is used to scan TVWS at a higher speed.

Up to now, diverse tunable filters have been proposed [2–10]. However, most designs suffer from narrow tuning ranges, un-

equal tuning bandwidths, or high insertion loss for narrow pass-band bandwidth. Hence, the tunable bandpass filters (BPF) design methods are not suitable for use in the TVWS band (470–698 MHz). Therefore, in this paper, we propose an efficient method, which covers a wide frequency range with narrow tuning bandwidths.

The tunable filter suggested in this paper switches 11 LC tank circuits through PIN diode to cover the whole TVWS band. In addition, while maintaining a constant bandwidth from 480 MHz to 680 MHz, it can be tuned at intervals of 20 MHz. With one varactor diode added, minute frequency tuning becomes possible. For efficient spectrum sensing, we have to design a BPF with a narrow bandwidth in order to reduce the noise floor. In such case the large insertion loss is inevitable due to the low Q resonant section. By adding the active capacitance circuit designed in broadband [11], we can effectively reduce the insertion loss.

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Manuscript received August 29, 2016 ; Revised January 5, 2017 ; Accepted January 12, 2017. (ID No. 20160829-032J)

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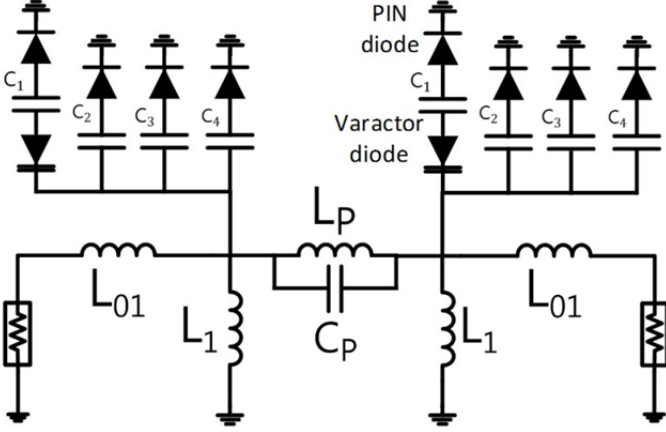


Fig. 1. The circuit of the proposed tunable BPF.

## II. DESIGN PROCEDURES

The tunable BPF proposed in this paper is derived from Chebyshev filter response, which is composed of lumped element resonators and an L-coupled structure is used [12] as shown in Fig. 1.

### 1. Tuning Method (Composition of Resonator)

The proposed filter uses the PIN diodes and a varactor diode to vary the capacitive loading on the LC resonant section of Fig. 1 to change the center frequency of the filter. The voltages applied to the PIN diodes which are operating as on/off switches connected to capacitors, allow the resonator to have an appropriate capacitance. The parasitic capacitance introduced by PIN diodes are added to the existing capacitor bank which results in the lowering the center frequency of the filter. For a minute frequency tuning a varactor diode is employed. In this way, one can tune each of the 11 channels at 20-MHz spacing in the 480–680 MHz band.

### 2. Design of the Constant Bandwidth Filter

When we design a BPF using lumped elements, the values of  $L$  and  $C$  of the resonant circuit can be arbitrarily determined as long as their product falls on the resonant frequency. However, the degree of coupling also depends on the LC product. In such a case the  $J$ -inverter value  $J_{12}$  is configured by inductor  $L_{12}$  as

$$J_{12} = \frac{1}{\omega_0 L_{12}} = BW C \sqrt{\frac{1}{g_1 g_2}}. \quad (1)$$

And the filter bandwidth can be expressed as

$$BW = \frac{\sqrt{g_1 g_2}}{\omega_0 L_{12} C} = \frac{\sqrt{L_{12} g_1 g_2}}{L_{12} \sqrt{C}}, \quad (2)$$

where  $C$  is the capacitance value of the resonator, which refers to the total capacitance including the capacitor bank. In addition,  $g_1$  and  $g_2$  refers to a low-pass filter prototype element values. In case the value of  $C$  changes in (2), the center frequen-

cy as well as the bandwidth will be changed. In order to maintain the bandwidth constant by compensating the capacitance variation, one can replace  $L_{12}$  by parallel LC circuit. Then one can derive the following relation:

$$L_{12} = \frac{L_p}{\sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}} \quad \text{or} \quad L_p = L_{12} \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}, \quad (3)$$

where  $L_p$  and  $C_p$  is the coupling elements in Fig. 1, and  $\omega_p = \frac{1}{\sqrt{L_p C_p}}$ . Next we derive the detailed condition for the constant bandwidth within the tuning frequency range. The maximum and minimum values of the bandwidth within the tuning range is derived as

$$BW_{max} = \frac{\sqrt{L_1 g_1 g_2}}{L_p \sqrt{C_{max}}} \sqrt{1 - \frac{\omega_0^2}{\omega_p^2}}, \quad (4)$$

$$BW_{min} = \frac{\sqrt{L_1 g_1 g_2}}{L_p \sqrt{C_{min}}} \sqrt{1 - \frac{\omega_0^2}{\omega_p^2}}. \quad (5)$$

Since the above two bandwidths are supposed to be the same, one can obtain the constant bandwidth condition as

$$\omega_p = \sqrt{\frac{1}{L_1} \left( \frac{1}{C_{max}} + \frac{1}{C_{min}} \right)}, \quad (6)$$

$$C_p = \frac{1}{\omega_p^2 L_p}. \quad (7)$$

Thus when the inverter that connects the resonators is replaced by an LC parallel circuit as in Fig. 1, it is possible to maintain a constant bandwidth. In Fig. 2 we plotted the constant bandwidth condition together with the conventional L-coupled case, both of which were simulated through MATLAB.

Fig. 3 shows the measured frequency characteristics of the designed tunable BPF which the center frequency  $f_0$  of the 11 channels is also given in this figure and the 3-dB bandwidth of each channel was measured as 25 MHz. The BPF was constructed on the FR-4 substrate ( $\epsilon_r = 4.3$ ) of a 1.6-mm thickness. The measured insertion loss lies between 2.8 and

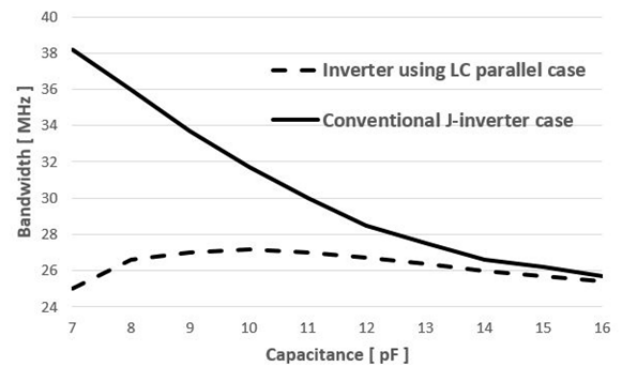


Fig. 2. Simulated bandwidth using MATLAB calculation (capacitance versus bandwidth).

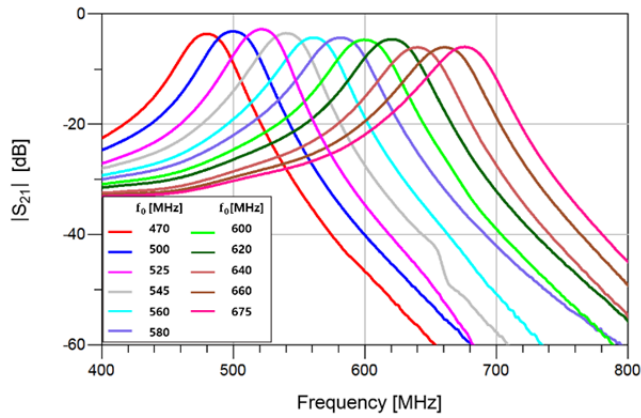


Fig. 3. Measured  $S$ -parameters of the proposed tunable BPF.

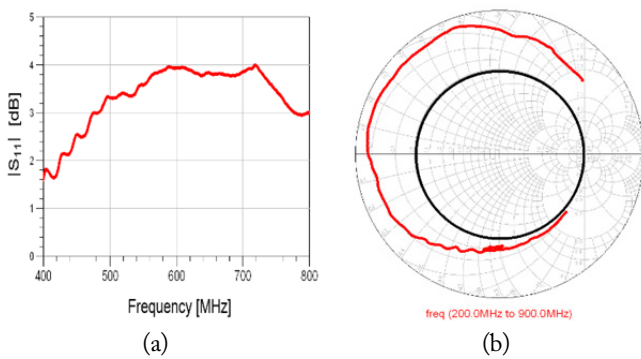


Fig. 4. (a) Measured frequency response of the active capacitance circuit and (b) its input impedance variations (black solid line is unit circle).

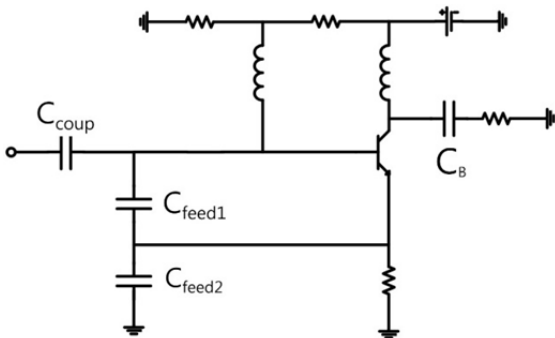


Fig. 5. The active capacitance circuit employed.

6.1 dB. As the frequency becomes higher, the insertion loss increases, because the  $Q$  of the resonator is reduced.

### III. DESIGN OF ACTIVE TUNABLE BPF

Since the quality factor of the resonant circuit is low, the proposed tunable BPF suffers a relatively high insertion loss. Therefore, we added an active capacitance circuit that compensates for the insertion loss. We modified the active capacitance circuit given in [11] in order to acquire the negative resistance within the wide TVWS band. Since the insertion loss becomes larger

as the frequency goes higher, the value of the negative resistance must also be larger as the frequency goes higher, as shown in Fig. 4. In Fig. 5 the capacitor  $C_{coup}$  is inserted for the coupling between the tunable BPF and the active capacitance circuit. This capacitor affects the magnitude and phase variation of the reflection coefficient of the negative circuit.

Therefore, we chose the magnitude of the negative resistance in such a way that the accompanied capacitor does not affect the resonant frequencies very much [11].

### IV. SIMULATED AND MEASURED RESULTS

By combining the active capacitance circuit and the resonator of the tunable BPF, we can design the active tunable BPF, as shown in Fig. 6. In this process, about 0.1 pF from the active capacitance circuit element from the active circuit is added to the resonator so that the resonant frequency of the filter is shifted 4.8 MHz. In this paper, a varactor diode was also used to compensate for this frequency shifts. Also, the capacitance from the PIN diode and substrate cannot be ignored so that we should be considered before synthesizing. We measured the parasitic capacitance of the PIN diode and the substrate and included it to the capacitor bank.

A comparison of the simulated and the measured results for 3 selected channels is shown in Fig. 7. The simulation results are obtained by Keysight Technologies' Advanced Design System (ADS) 2014.

In the proposed active tunable BPF, we use the BFP620 BJT of Infineon Corporation in order to obtain the negative resistance, and the design values of the lumped elements are presented in Table 1. The filter was fabricated on the FR-4 substrate with a thickness of 1.6 mm, a dielectric constant of 4.3, and a tangent loss of 0.022. Fig. 3 shows the frequency responses of the designed tunable BPF without the compensation of the loss by the active circuit. In this case the maximum insertion loss within the whole tuning range reaches 6.07 dB. Contrary, Fig. 8(a) and (b) show the filter performances which is compensated by the active circuit. By adding the active capacitance circuit, the insertion loss has been measured less than 2.0 dB within the whole tuning range. The 1-dB bandwidth for each tuning frequency is a 25-MHz bandwidth within a tolerance of approximately 5%. The measured characteristics of BPF with active capacitance compensation show that the tenability remains almost the same as the one given in Fig. 3. The PIN diode used in this design is M/A-COM's MA4P504-1072T, and the bias voltage for the PIN diode is applied to a 1.1 V. The varactor diode is Toshiba's 1SV270. By adding the active capacitance circuit, much more efficient and accurate spectrum sensing is available. The measured OIP3 at each tuning frequency of the

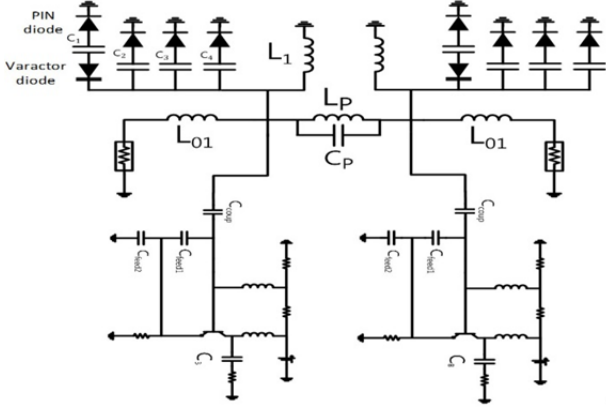


Fig. 6. The designed circuit of proposed active tunable BPF.

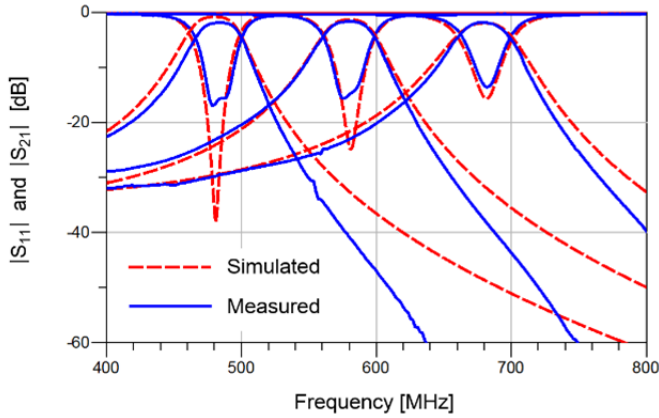

 Fig. 7. Comparison of frequency characteristics ( $|S_{11}|$  and  $|S_{21}|$ ) for 3-selected channels.

Table 1. Element values of the designed circuit

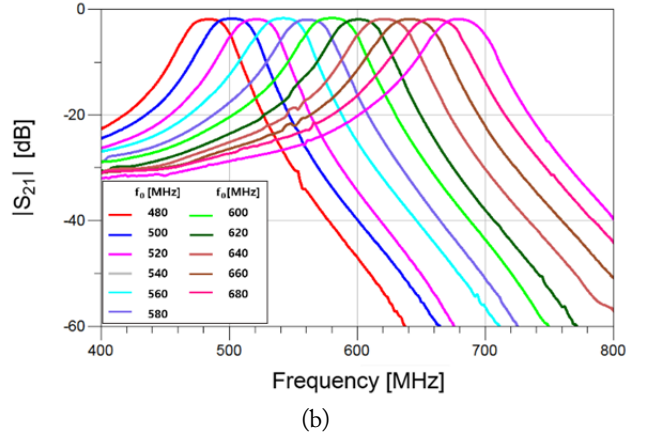
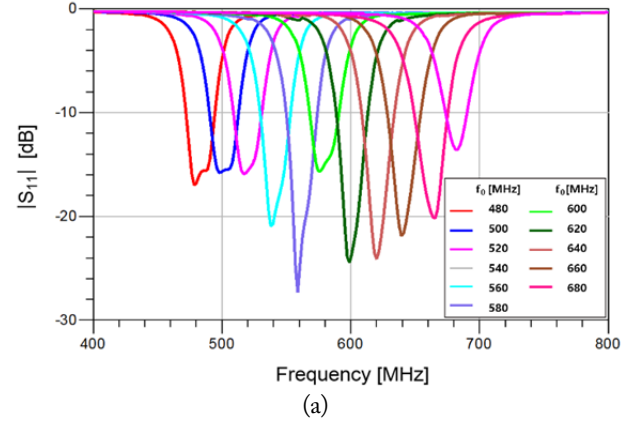
Element	Value	Element	Value
$C_1$	5 pF	$L_1$	9.5 nH
$C_2$	2.5 pF	$L_{01}$	50 nH
$C_3$	3 pF	$L_p$	132 nH
$C_4$	4 pF	$C_{feed1}$	3 pF
$C_p$	0.25 pF	$C_{feed2}$	9 pF
$C_{coup}$	82 pF	$C_c$	27 pF

TVWS band has values of 19.33–20.83 dB. Compared to the typical OIP3 of BFP620 used to constitute the active capacitance circuit, it can be seen as a reasonable value.

The center frequency of the tunable bandpass filter is controlled by MATLAB and the value of the required capacitor value for each tuning channel is constituted by a lookup table.

## V. CONCLUSION

In this paper, we present an active tunable BPF that has a constant bandwidth and 11 channels to cover the TVWS (470–690 MHz) band for the efficient spectrum sensing application. The designed tunable BPF employs the lumped elements, and


 Fig. 8. Measured  $S$ -parameters of the proposed active capacitance tunable BPF. (a)  $|S_{11}|$  and (b)  $|S_{21}|$  in dB.

the frequency tuning is done by switching the capacitance in the capacitor bank comprised of PIN diodes and a varactor diode. In order to reduce the insertion loss, the active capacitance circuit was coupled to the tunable BPF. Simulated and measured results confirmed the performances of the tunable BPF having a small insertion loss of less than 2 dB in the wide TVWS band.

This research was supported by the Ministry of Science, ICT & Future Planning (MSIP), Korea, in the ICT R&D Program 2014 (No. B0101-14-0171).

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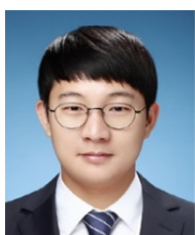
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