JOURNAL OF ELECTROMAGNETIC ENGINEERING AND SCIENCE, VOL. 13, NO. 4, 245－250, DEC. 2013

http://dx.doi.org/10.5515/JKIEES.2013.13.4.245
ISSN 2234-8395 (Online) · ISSN 2234-8409 (Print)

Tunable Bandpass Filter with Varactors Based on the CRLH-TL Metamaterial Structure

Beom Kyu Kim · Bomson Lee*

Abstract

This paper presents a tunable bandpass filter based on the varactor-loaded composite right- and left-handed transmission line (CRLH-TL). The proposed filter is composed of one CRLH-TL unit cell, which corresponds to the third-order bandpass filter. The tunable bandpass filter is designed using only lumped-elements. The use of lumped elements saves space and lowers the fabrication cost. The size of the proposed tunable bandpass filter is 17 mm × 5 mm, neglecting the feed lines and DC lines. All of the varactors are controlled by one DC bias. The center frequency of the bandpass filter can be controlled by varying the value of the varactors. The tunable range of the center frequency is from 412.5 to 670 MHz. The insertion loss is less than 3 dB, the return loss is more than 10 dB in the passband.

Key Words: CRLH, Filter, Metamaterial, Varactor Diode.

Ⅰ. Introduction

There has been intense research on metamaterial (MTM)-based transmission lines. The structure and theory of one-dimensional (1D) composite right- and left-handed transmission lines (CRLH-TLs) have been studied and analyzed a great deal [1－4]. The conventional transmission lines, which support transverse electromagnetic waves and follow the right-hand rule, have been characterized by the distributed series inductance L (given in units of H/m) and shunt capacitance C (given in units of F/m). The 1D MTM lines can be constructed by periodically loading series capacitors and shunt inductors on TLs [1]. These MTM lines have been employed to build compact wideband phase shifters, filters, and other electromagnetic devices [2]. The tunable bandpass filter (BPF) is an essential element to extract signals in modern multimode and multiband communication systems. Tunable filters are a great of interest for the design of multi-functional wireless, cognitive radio, and satellite communication systems. Most tunable BPFs are composed of resonator circuits with a voltage-variable capacitor as a tuning element [5－11]. Two kinds of voltage-variable capacitors are in common use. One type is a conventional varactor [5, 6], and the other is a microelectromechanical system (MEMS) bridge [7, 8]. The tunable BPFs using the MEMS technique have an advantage in terms of loss. However, a very high DC bias voltage must be applied to control the bridge height, and MEMS-based BPFs are slow. Often, it is expensive to fabricate the MEMS. Therefore, MEMS-based BPFs are not ideal for commercial wireless applications. In contrast, tunable BPFs with varactors show faster tuning speeds and lower voltage operation. However, because of the low Q varactors, insertion loss inside the passband can be larger in tunable BPFs with the varactor. In controlling the center frequency of the conventional tunable BPFs, the series and parallel resonant frequencies must be controlled simultaneously. Thus, the BPFs should have two DC biases. In [9], the center frequency of the BPF can be tuned from about 0.45

Manuscript received November 14, 2013 ; Revised December 11, 2013 ; Accepted December 12, 2013. (ID No. 20131114-047J)
Department of Electronics and Radio Engineering, College of Electronics and Information, Kyung Hee University, Yongin, Korea.
*Corresponding Author: Bomson Lee (e-mail: bomson@khu.ac.kr)

to 0.65 GHz. Because the center frequency is controlled by varying the upper cutoff frequency, the tuning range of the center frequency is slightly narrow. However, the fractional bandwidth, which has a wide range, is about 36%. The size of the fabricated circuit is about 30 mm × 5 mm.

In this paper, despite the lossy substrate (FR4), a BPF with a compact size and low-insertion loss is proposed. Although the proposed BPF has a narrow fractional bandwidth, a wide tunable range of the center frequency can be obtained by varying the center frequency independently. Furthermore, the proposed tunable BPF has only one DC bias to control the center frequency. The presented tunable filter is for applications in the ISM band (400 MHz) and LTE band (800 MHz), but may easily be modified for other applications using different bands.

Ⅱ. THEORY

Fig. 1 shows that the conventional CRLH-TL has a periodic structure with multiple cells. Fig. 2 shows one cell of the conventional CRLH-TL in the form of a T-symmetric equivalent circuit. C_L and L_L have a left-handed property and C_R and L_R have a right-handed property. In the prototype design, the source and the load resistances are unity (except for equal-ripple filters with an even N, which have non-unity load resistance).

The source resistance of R_S can be obtained by multiplying the impedances of the prototype design by R_0. If we let primed variables denote the impedance scaled quantities, the new filter element values are given by

$$L' = R_0 L,$$

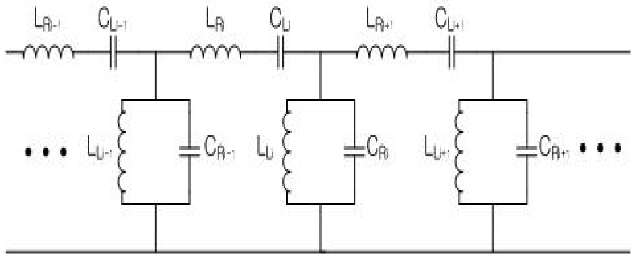


Fig. 1. Circuit model of the periodic composite right- and left-handed transmission line.

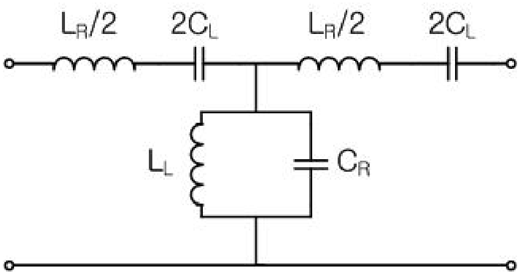


Fig. 2. T-equivalent circuit of one cell composite right- and left-handed transmission line (three stages).

$$C' = \frac{C}{R_0},$$
$$R_S' = R_0,$$
$$R_L' = R_0 R_L \tag{1}$$

where L, C, and R_L are the values given in the original prototype.

If ω_1 and ω_2 denote the lower and upper cutoff frequencies of the passband, a bandpass response can be obtained by using the following frequency substitution:

$$\omega \leftarrow \frac{\omega_0}{\omega_2 - \omega_1}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) = \frac{1}{\Delta}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$
$$(\Delta = \frac{\omega_2 - \omega_1}{\omega_0}) \tag{2}$$

where Δ is the fractional bandwidth of the passband.

The new filter elements are determined using (2) in the expressions for the series reactance and shunt susceptance. Thus,

$$jX_k = \frac{j}{\Delta}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) L_k$$
$$= j\frac{\omega L_k}{\Delta \omega_0} - j\frac{\omega_0 L_k}{\Delta \omega} = j\omega L_k' - j\frac{1}{\omega C_k'} \tag{3}$$

which shows that a series inductor given in the low-pass prototype, L_k, is transformed to the series LC circuit with element values by

$$L_k' = \frac{L_k}{\Delta \omega_0},$$
$$C_k' = \frac{\Delta}{\omega_0 L_k}. \tag{4}$$

In the same manner, a shunt capacitor given in the low-pass prototype, C_k, is transformed to the shunt LC circuit with element values by

$$L_k' = \frac{\Delta}{\omega_0 C_k},$$
$$C_k' = \frac{C_k}{\Delta \omega_0}. \tag{5}$$

When the center frequency is 0.8 GHz, the values of the inductors and capacitors (C_L = 0.202 pF, L_L = 1.1 nH, C_R = 36 pF, and L_R = 196 nH) through impedance scaling and frequency transformation are given by

$$L_R = \frac{L_k Z_0}{\omega_0 \Delta},\ C_R = \frac{\Delta}{\omega_0 L_k Z_0}$$

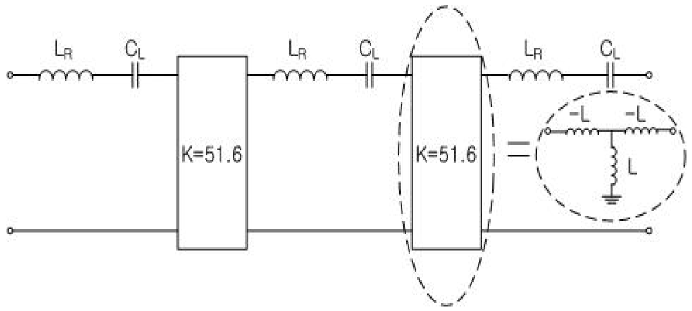


Fig. 3. Equivalent circuit using the impedance inverters of one composite right- and left-handed transmission line cell.

$$L_L = \frac{\Delta Z_0}{\omega_0 C_k},\ C_L = \frac{C_k}{\omega_0 \Delta Z_0}$$
$$(\Delta = \frac{\omega_2 - \omega_1}{\omega_0}, \omega_0 = \frac{1}{\sqrt{L_R C_R}} = \frac{1}{\sqrt{L_L C_L}}) \tag{6}$$

where ω_0 is the center frequency, L_k and C_k are the element values for the low-pass prototype circuit, and Z_0 is the source impedance.

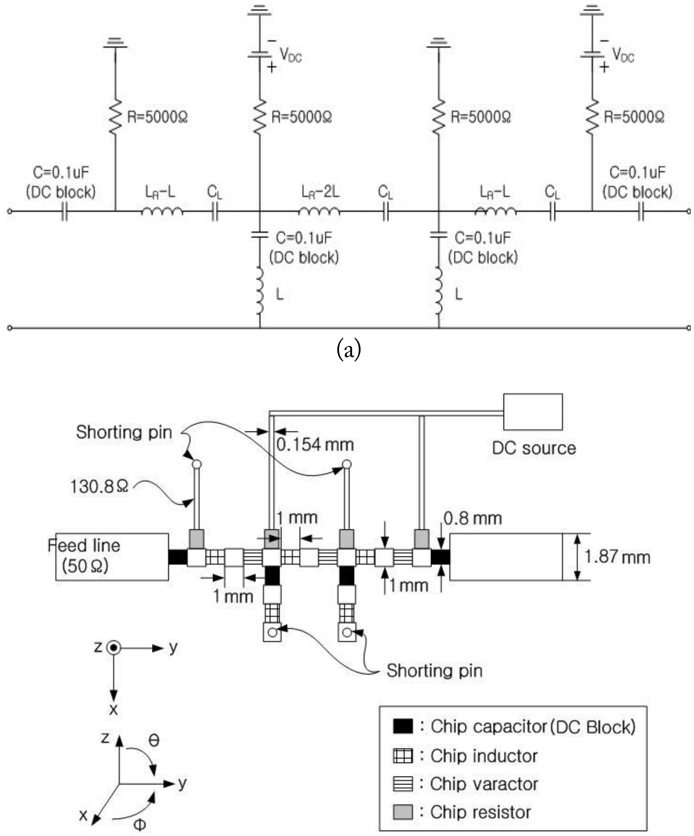
Fig. 3 shows an equivalent circuit using inverters of Fig. 2. In it, lumped inductors can be used instead of impedance inverters. The use of lumped elements saves space and lowers the fabrication cost. By using inverters, an identical series tuned resonator can be substituted for the parallel resonant circuit section of the BPF. Therefore, all of the varactors are controlled by the same voltage. The value of the K-inverter in Fig. 3 is given by

$$j\omega C_R(1-\frac{\omega_0^2}{\omega^2}) = Y^2 j\omega L_R(1-\frac{\omega_0^2}{\omega^2}) \Rightarrow J = \sqrt{\frac{C_R}{L_R}}$$
$$K = \frac{1}{J} = \omega L \tag{7}$$

where, J is an admittance inverter ($K = 51.6$), L is the inductor in the lumped-element K-inverter ($L = 10.26$ nH), and ω_0 is the angular design frequency ($f_0 = 0.8$ GHz).

Ⅲ. Design of the CRLH Type Tunable BPF

Fig. 4(a) shows the circuit of the proposed CRLH-TL type tunable BPF using the lumped-inverters and DC biases. Fig. 4(b) shows the geometry of the proposed CRLH-TL type tunable BPF. It is constructed using microstrip lines on an FR-4 substrate (with a relative permittivity of 4.6 and a height of 1 mm). The circuit was built with lumped-elements and varactors, resulting in a compact size. The two inverters, a series capacitor, and a series inductor are substituted for the parallel resonant circuit at the T-equivalent circuit of one CRLH-TL cell. After the substitution, all of the series capacitors are replaced with the varactors, and the inverters are replaced with lumped elements. Therefore, the center frequency of the BPF is controlled by varactors of the same value.



(a)

(b)

Fig. 4. The proposed tunable bandpass filter. (a) Circuit and (b) geometry.

The simulation software used in this paper is CST STUDIO SUITE (Computer Simulation Technology AG, Darmstadt, Germany). The design frequency is 0.8 GHz. The diameter of the via hole is 0.5 mm. The size of the BPF is approximately 15 mm × 5 mm, neglecting the feed and DC lines. The impedances of the feed and DC lines are 50 Ω and 130.8 Ω, respectively. The width of the feed line is 1.87 mm. The other dimensions are depicted in Fig. 4(b). To provide a DC block to the shunt inductors and the feed lines, four chip capacitors (0.1 μF) were put into the structure, as shown in Fig. 4.

Fig. 5 shows the simulated insertion loss variation graph versus the number of stages at 0.8 GHz. The slope of the stopband attenuation can be made steeper by increasing the number of cells. However, the insertion loss inside the passband can be larger.

Fig. 6 shows the insertion loss and return loss variation versus the value of the resistance at 0.8 GHz. To prevent the radio frequency (RF) signal from flowing into the DC lines, the resistor should be much larger than 50 Ω. Therefore, 5 kΩ chip resistors were used to give the proper DC voltage to the chip varactors. A large resistance value reduces the insertion loss at the expense of the total circuit size, especially when it is made as a monolithic microwave integrated circuit. The used varactor is the SMV1265-011LF hyper-ab-

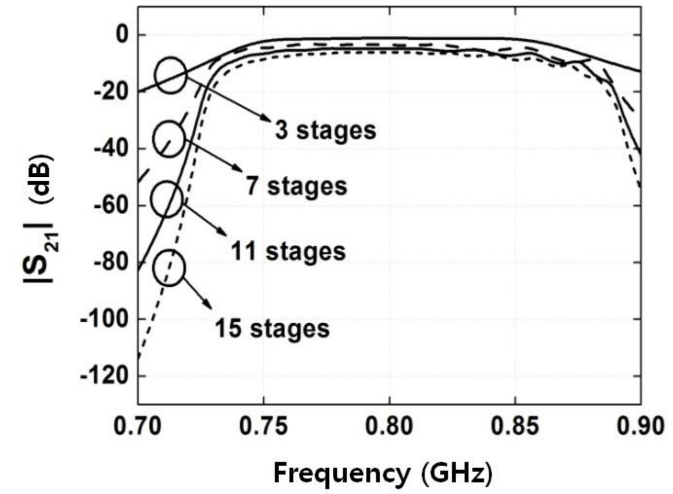
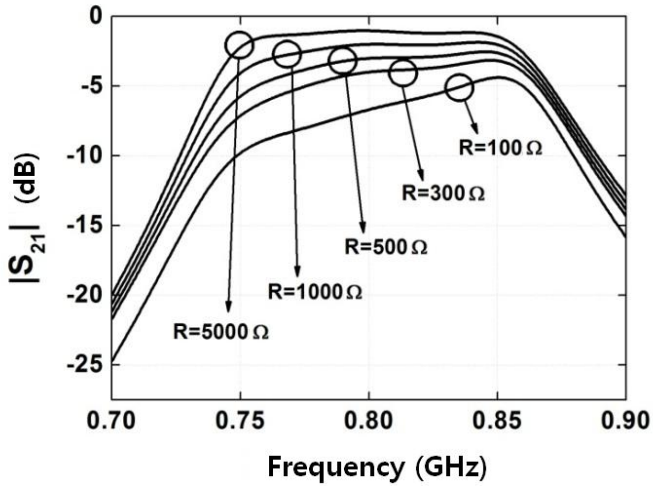
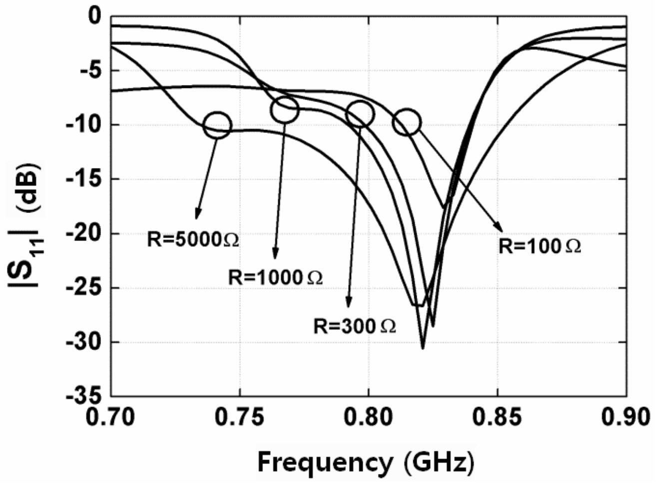


Fig. 5. The electromagnetic-simulated insertion loss versus the resistance value at 0.8 GHz.



(a)

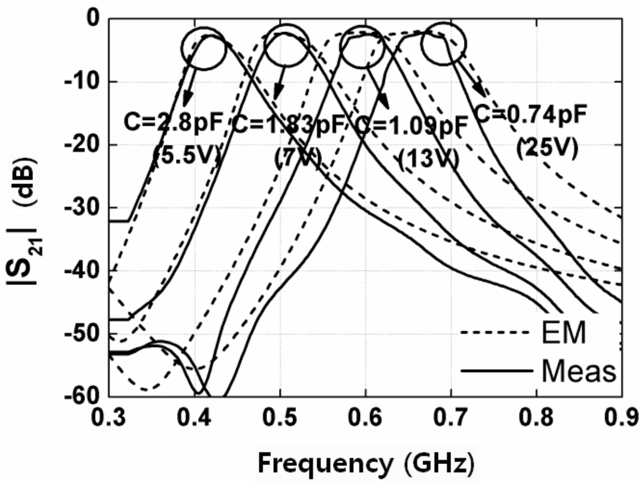


(b)

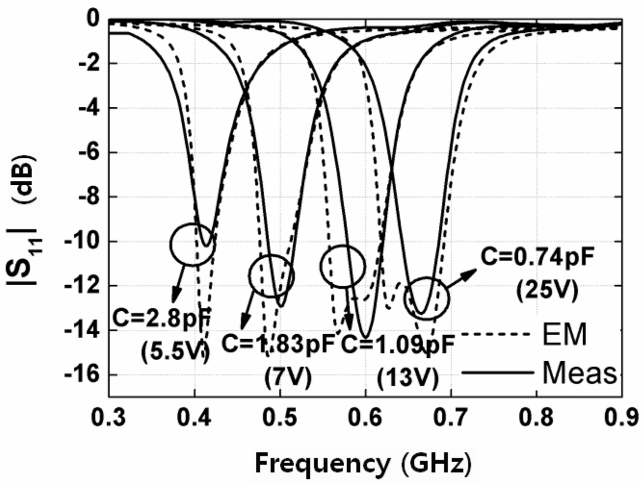
Fig. 6. The electromagnetic-simulated insertion loss and return loss versus the resistance value at 0.8 GHz. (a) $|S_{21}|$ and (b) $|S_{11}|$.

rupt junction varactor diode from Skyworks Solution Inc. to control the center frequency-C(V_{bias} = 0 V) = 22.47 pF, C(V_{bias} = 5 V) = 3.38 pF, C(V_{bias} = 7 V) = 1.86 pF, C(V_{bias} = 14 V) = 1.05 pF, C(V_{bias} = 26 V) = 0.73 pF, and C(V_{bias} = 30 V) = 0.71 pF. The series resistance in the varactor is 2.4 Ω.

Fig. 7 shows the comparison between the EM-simulated and measured *S*-parameters versus the values of the chip varactor. Fig. 7(a) shows the magnitude of S_{21}, and Fig. 7(b) shows the magnitude of S_{11}. In the measured results, the insertion loss is slightly larger than in the EM-simulated result. This may be because the varactors and inductors have large series resistance. As shown in Fig. 7, the center frequency of the BPF can be tuned from about 410 to 670 MHz, which can be increased by using the appropriate varactor model with small series resistance. When the value of the varactors is 0.74 pF, the center frequency (f_0), 3-dB bandwidth (BW), and fractional bandwidth (FBW) are 670 MHz, 42.5 MHz, and 6.3%, respectively. When the value of the varac-



(a)



(b)

Fig. 7. *S*-parameters of the proposed bandpass filter versus the chip varactor values. (a) $|S_{21}|$ and (b) $|S_{11}|$. EM = electromagnetic-simulated, Meas = measured.

Table 1. Summary of center frequency (f_0) and bandwidth versus the varactor values (C)

C (pF)	f_0 (MHz)	3-dB BW (MHz)	FBW (%)
2.8	412.5	15	3.6
1.83	500	22.5	4.5
1.09	600	35	5.8
0.74	670	42.5	6.3

BW = bandwidth, FBW = fractional bandwidth.

Table 2. Comparison between the proposed filter and conventional ones

Ref.	Size (mm^2)	Insertion loss (dB)	Range of tuned center frequency (MHz)
[9]	30 × 5	3	200
[10]	30 × 8	2.8 – 4.6	300
[11]	63 × 43	5	500
[12]	33 × 28	4	600
This work	17 × 5	3	260

tors is 1.09 pF, the center frequency (f_0), 3-dB BW, and FBW are 600 MHz, 35 MHz, and 5.8%, respectively. When the value of the varactors is 1.83 pF, the center frequency (f_0), 3-dB BW, and FBW are 500 MHz, 22.5 MHz, and 4.5%, respectively. When the value of the varactors is 2.8 pF, the center frequency (f_0), 3-dB BW, and FBW are 412.5 MHz, 15 MHz, and 3.6%, respectively. Based on the FBW of about 4.5% – 6%, the center frequency is tuned from about 500 to 670 MHz. Regardless of maintaining the FBW, the center frequency can be tuned with a range of 260 MHz when the value of the varactors is 2.8 pF. The insertion loss and the return loss in all cases are less than 3 dB and more than 10 dB in the passband, respectively.

Table 1 shows the summary of the center frequency, 3-dB BW, and FBW versus the chip varactor values.

Table 2 shows the comparison between the proposed filter and the conventional ones in terms of size, insertion loss, and a tunable range of the center frequency.

Ⅳ. Conclusion

A tunable BPF based on the varactor-loaded MTM line is proposed, and the detailed theory concerning its operation is discussed. By using inverters, series-tuned resonators are substituted for the parallel resonant circuit section of the BPF. All of the varactors that are substituted for the capacitors are controlled by the same voltage of one DC bias. Therefore, the center frequency of the BPF is controlled by varactors of the same value. In addition, lumped elements replaced the inverters to save space and to lower the fabrication cost. Considering that the FBW is maintained between 4.5% – 6%, the tunable range of the center frequency is around 170 MHz. Otherwise, the tunable range of the center frequency is around 260 MHz. The results of the EM-simulation and the measurements show good agreement. The circuit size was compact (17 mm × 5 mm), since only lumped elements were used to design the device. The insertion loss of the proposed BPF is less than 3 dB, despite the high loss of the FR4 substrate, and the return loss is more than 10 dB in the passband.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (No. 2013015202).

References

[1] G. V. Eleftheriades, A. K. Iyer, and P. C. Kremer, "Planar negative refractive index media using periodically L-C loaded transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 12, pp. 2702 – 2172, Dec. 2002.

[2] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. New York, NY: John Wiley & Sons, 2006.

[3] S Lim, C. Caloz, and T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 1, pp. 161 – 173, Jan. 2005.

[4] C. Caloz and T. Itoh, "Transmission line approach of left-handed (LH) materials and microstrip implementation of an artificial LH transmission line," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 5, pp. 1159 – 1166, May 2004.

[5] B. W. Kim, Y. H. Chun, and S. W. Yun, "Varactor-tuned active bandpass filter with low noise performance," *IEEE Electronics Letters*, vol. 40, no. 15, pp. 945 – 946, Jul. 2004.

[6] S. R. Chandler, I. C. Hunter, and J. G. Gardiner, "Active varactor tunable bandpass filter," *IEEE Microwave and Guided Wave Letters*, vol. 3, no. 3, pp. 70 – 71, Mar. 1993.

[7] H. T. Kim, J. H. Park, Y. K. Kim, and Y. Kwon, "Low-loss and compact V-band MEMS-based analog tunable bandpass filters," *IEEE Microwave and Wireless Components Letters*, vol. 12, no. 11, pp. 432 – 434, Nov. 2002.

[8] Y. Liu, A. Borgioli, A. S. Nagra, and R. A. York, "Distributed MEMS transmission lines for tunable filter applications," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 11, no. 5, pp. 254 – 260, Sep. 2001.

[9] A. S. Mohra and O. F. Siddiqui, "Tunable bandpass filter based on capacitor-loaded metamaterial lines," *IEEE Electronics Letters*, vol. 45, no. 9, pp. 470 – 472, Apr. 2009.

[10] A. L. Borja, J. Carbonell, J. D. Martinez, V. E. Boria, and D. Lippens, "A controllable bandwidth filter using va-

ractor-loaded metamaterial-inspired transmission lines," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1575–1578, 2011.

[11] C. Reck, R. Trommer, and L. Schmidt, "Bandpass filter with tunable bandwidth and center frequency based on varactor diodes," in *Proceedings of the 6th German Microwave Conference*, Darmstadt, Germany, 2011.

[12] J. Long, C. Li, W. Cui, J. Huangfu, and L. Ran, "A tunable microstrip bandpass filter with two independently adjustable transmission zeros," *IEEE Microwave and Wireless Components Letters*, vol. 21, no. 2, pp. 74–76, Feb. 2011.

Beom Kyu Kim

received a B.S. degree in electronics and radio engineering from Kyung Hee University, Yongin, Korea, in 2012, where he is currently working toward his M.S. degree. His fields of research include microwave antennas, passive devices, and metamaterials.

Bomson Lee

received a B.S. degree in electrical engineering from Seoul National University, Seoul, Korea, in 1982, and M.S. and Ph.D. degrees in electrical engineering from the University of Nebraska, Lincoln, in 1991 and 1995, respectively. From 1982 to 1988, he was with Hyundai Engineering Company Ltd., Seoul, Korea. In 1995, he joined the faculty at Kyung Hee University, where he is currently a professor with the Department of Electronics and Radio Engineering. He was an Editor-in-Chief of the Journal of the Korean Institute of Electromagnetic Engineering and Science in 2010. He is an Executive Director (Project) at the Korea Institute of Electromagnetic Engineering & Science (KIEES). His research activities include microwave antennas, RF identification (RFID) tags, microwave passive devices, wireless power transmission, and metamaterials.