[20] Byambaakhuu B, et al. Development of small-sized UWB antenna for binaural hearing AIDS. *Microwave Opt Technol Lett.* 2015;57(8):1883–1889.

[21] Tofighi, Mohmmad-Reza. "Characterization of biomedical antennas for microwave heating, radiometry, and implant communication applications. In: "*IEEE 12th Annual Wireless and Microwave Technology Conference (WAMICON)*, 2011

[22] Klemetsen Ø, Jacobsen S. Improved radiometric performance attained by an elliptical microwave antenna with suction. *IEEE Trans Biomed Eng.* 2012;59(1):263–271.

How to cite this article: Byambaakhuu B, Nyamsuren P, Park R-, Cheon C. Monostatic radiometry system for temperature measurement during RF hyperthermia treatment. *Microw Opt Technol Lett*. 2017;59:2262–2272. https://doi.org/10.1002/mop.30725

Received: 25 January 2017

DOI: 10.1002/mop.30724

Size reduction of composite right/left handed transmission line and its application to the design of dual-band bandpass filter

Boram An | **Girdhari Chaudhary** | **Yongchae Jeong**

Division of Electronics and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea

Correspondence
Division of Electronics and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea.
Email: ycjeong@jbnu.ac.kr

Abstract

This article presents a method that chooses appropriate phase size to reduce the size of a composite right/left-handed (CRLH) transmission line. A reduced-size dual-band bandpass filter was designed and fabricated to demonstrate the proposed CRLH line, and the wide dual-passband characteristics are obtained by implementing a dual-band J-inverter as the coupling between 2 CRLH-resonators. A defected ground structure is adopted to obtain the line with a high characteristic impedance for the J-inverter. The designed dual-wideband bandpass is validated by conducting experiments and obtaining measures of its performance. The results show that the 2 passbands are centered at 2.4 GHz and 5.2 GHz, with a 3-dB fractional bandwidth of 33.75% and 38.46%, respectively. In addition, this filter has low insertion losses of 0.21 dB and 0.5 dB for each passband.

KEYWORDS

defected ground structure, dual-band J-inverter, dual wide bandwidth, reduced composite right/left-handed transmission line

1 | INTRODUCTION

The miniaturization of circuits has become an important design issue due to the rapid development of wireless communication systems, and multi-band systems have now been introduced. As such, multi-bandpass filters play an important role in the circuit miniaturization of wireless communication system, and various types of dual-band bandpass filters have been studied in the existing literature.

Previously, a simple method to design dual-band filters was to connect 2 filters with different bands in cascade. However, the circuit size would increase when this method was used.[1] Similarly, 2-step frequency transformations had been applied to a low pass prototype to design dual-band filters.[2] Also, dual-band bandpass filters can be realized by using multi-mode resonators, such as a meander-loop resonator,[3] stepped impedance resonators (SIRs),[4] and microstrip open-loop resonators.[5] In recent years, composite right/left-handed (CRLH) transmission lines (TLs), which have a unique phase response, have been widely used to design multi-band microwave circuits.[6-8] However, conventional CRLH TLs used a phase response of $-\phi$ and -3ϕ at 2 frequency bands, which resulted in a large circuit size.

This article presents a size reduction for CRLH by choosing the appropriate phase response, such as ϕ and $-\phi$ at 2 frequency bands f_1 and f_2 ($f_2 > f_1$). The proposed method is used to reduce the circuit size of conventional CRLH TLs by up to 70%, depending on the frequency ratio (f_2/f_1) between the 2 frequency bands. A size-reduced dual-band filter was designed and fabricated to demonstrate the proposed CRLH TLs. In this work, short-stub CRLH TLs with dual-band resonator behavior are employed, and the coupling between the resonators is implemented using a π-type dual-band J-inverter consisting of an open-stub and TL. To realize lines with a high characteristic impedance, defected ground structures (DGSs) are adopted at the open stubs of dual-band J-inverters. Simple design equations are offered to find the element values of CRLH and the dual-band J-inverters at the given frequency specification. The proposed dual-wideband bandpass filter was simulated, fabricated, and measured at center frequencies of 2.4 GHz and 5.2 GHz to validate the design equations.

2 | DESIGN EQUATION

2.1 | Size reduction of a composite right/left-handed transmission line

CRLH TLs are generally implemented by combining right-handed (RH) TLs and left-handed (LH) TLs, as shown in Figure 1.[9] The phase responses of CRLH TLs (ϕ_{CRLH}) can be expressed as the sum of the phase responses of RH TLs (ϕ_{RH}) and LH TLs (ϕ_{LH}).

$$\phi_{CRLH}=\phi_{RH}+\phi_{LH}=-2\pi fN\sqrt{L_{RH}C_{RH}}+\frac{N}{2\pi f\sqrt{L_{LH}C_{LH}}}, \quad (1)$$

where N refers to the number of CRLH unit cells. In the case of conventional RH TLs, the second passband center frequency is determined to be 3 times the first passband center frequency ($f_2 = 3f_1$). However, in the case of CRLH TLs, the first and second passband center frequencies can be arbitrarily chosen ($f_2 \neq 3f_1$) because the phase response of the CRLH TLs is controlled by the values of L_{RH}, C_{RH}, L_{LH}, and C_{LH}. Since the RH part can be implemented using a normal microstrip line and an LH part with lumped elements, it is meaningful to reduce the size of the RH TLs. The length of the RH TL can be determined through $P=2\pi N\sqrt{L_{RH}C_{RH}}$, so Equation (1) can be expressed as Equation (2) by separating the phase response of the CRLH (ϕ_{CRLH}) at the 2 center frequencies (f_1 and f_2), respectively.

$$\begin{cases} \phi_{CRLH}^{f_1}=-f_1P+\dfrac{N}{2\pi f_1\sqrt{L_{LH}C_{LH}}} \\ \phi_{CRLH}^{f_2}=-f_2P+\dfrac{N}{2\pi f_2\sqrt{L_{LH}C_{LH}}} \end{cases}. \quad (2)$$

If $\phi_{CRLH}^{f_1}=-\phi$ and $\phi_{CRLH}^{f_2}=-3\phi$, P can be found as Equation (3) by solving Equation (2) simultaneously.

$$P=\phi\frac{3f_2-f_1}{f_2{}^2-f_1^2}. \quad (3)$$

On the contrary, if the $\phi_{CRLH}^{f_1}=\phi$ and $\phi_{CRLH}^{f_2}=-\phi$, P' instead of P can be found as Equation (4).

$$P'=\phi\frac{1}{f_2-f_1}. \quad (4)$$

From Equations (3) and (4), the size reduction factor (P'/P) is given by Equation (5).

$$\text{size reduction factor}=\frac{P'}{P}=\frac{f_2+f_1}{3f_2-f_1}=\frac{\alpha+1}{3\alpha-1}, \quad (5)$$

where $\alpha = f_2/f_1$ and is always $\alpha > 1$. Figure 2 shows a reduction factor of the proposed CRLH line as compared to a conventional CRLH. Since P' is always smaller than P, the size of RH TLs can be reduced between 42.8%and 71.4%, as compared to a conventional method depending on the frequency ratio, as shown in Figure 2.

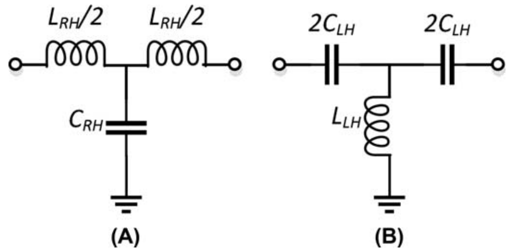

FIGURE 1 Unit cells of artificial (A) RH and (B) LH TLs

The equations for the element values of the LH TL part are given in Ref. [9] as

$$L_{LH}=\frac{NZ_{CRLH}\left[1-(\omega_1/\omega_2)^2\right]}{\omega_1[\phi_1-\phi_2(\omega_1/\omega_2)]}, \quad C_{LH}=\frac{N\left[1-(\omega_1/\omega_2)^2\right]}{\omega_1Z_{CRLH}[\phi_1-\phi_2(\omega_1/\omega_2)]} \quad (6)$$

where Z_{CRLH} is a characteristic impedance of CRLH TL.

2.2 | Application of reduced CRLH to design of dual-band bandpass filter

A short stub CRLH TL for $N = 2$ is used as dual-band resonator for the dual-band filter, as shown in Figure 3A. The equivalent TL model of the short stub CRLH resonator is shown in Figure 3B assuming $Z_{RH} = Z_{LH} = Z_{CRLH}$ and $\theta_{CRLH} = 2\theta_{RH} + \theta_{LH}$. The input admittance ($Y_{IN}$) of the short stub is given as Equation (7).

$$Y_{IN}=-j\frac{1}{Z_{CRLH}}\cot(\theta_{CRLH}), \quad (7)$$

where θ_{CRLH} is an electrical length of CRLH TL that is the same as the magnitude of ϕ_{CRLH}. The susceptance slope parameters for the dual-band resonator can be obtained using Equation (8).

$$b_i=\frac{\omega_i}{2}\frac{dB_{IN}}{d\omega}\bigg|_{\omega=\omega_i}=\frac{1}{2Z_{CRLH}}(\theta_{CRLH})\csc^2(\theta_{CRLH}), \quad i=1,\ 2. \quad (8)$$

In this work, the topology of the second order dual-band bandpass filter is adopted. Therefore, 2 identical short stub CRLH resonators were used, and the coupling between the resonators was implemented using a dual-band J-inverter. The values of J_{01} and J_{23} are set to $1/Z_0$ for simplicity and miniaturization. To operate the dual-band J-inverter, the value of J_{12} should be the same at 2 center frequencies, and it is given as

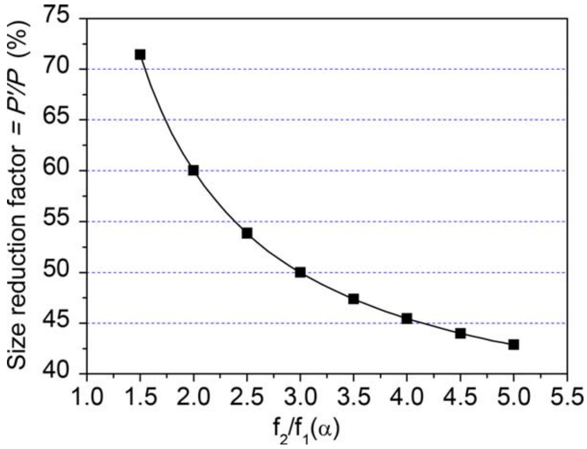

FIGURE 2 Size reduction factor of the proposed CRLH TLs with frequency ratio α, as compared to conventional ones. [Color figure can be viewed at wileyonlinelibrary.com]

$$J_{12}=\Delta_1\sqrt{\frac{b_1^2}{g_1g_2}}=\Delta_2\sqrt{\frac{b_2^2}{g_1g_2}}, \tag{9}$$

where Δ_1 and Δ_2 are 3-dB fractional bandwidth (FBW) at 2 center frequencies f_1 and f_2. The values b_1 and b_2 can be calculated by using Equation (8).

Figure 4 shows the structure of the implemented dual-band J-inverter consisting of π-type open stubs and series TL. The characteristic impedance and the electrical length of the open stubs are denoted as Z_1 and θ_1, respectively, whereas the series TL characteristic impedance and the electrical length are denoted as Z_2 and θ_2. The circuit parameter of the dual-band J-inverters[8] can be given as

$$Z_1=\frac{\tan\theta_1}{J_{12}\cos\theta_2},\quad Z_2=\frac{1}{J_{12}\sin\theta_2}, \tag{10}$$

$$\theta_1=\theta_2=\frac{\pi}{\alpha+1}=\frac{\pi f_1}{f_2+f_1}. \tag{11}$$

Figure 5 shows the characteristic impedance of the open stub (Z_1) of the dual-band J-inverter by varying the frequency ratio ($\alpha = f_2/f_1$) and assuming a different 3-dB FBW. As seen in this figure, the characteristic impedance of the open stubs is very high when 3-dB FBW is 30%, and the frequency ratio becomes smaller, such as 2. Since the characteristic impedance of the TL is high (>130 Ω), it is difficult to implement it in microstrip line technology. However, the

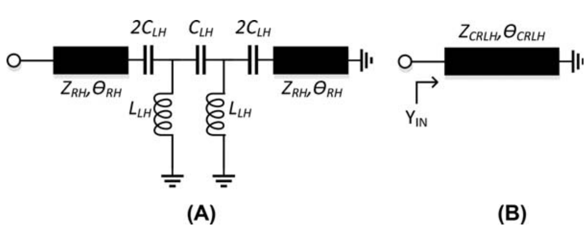

FIGURE 3 (A) Short stub CRLH for $N = 2$ and (B) its equivalent transmission line model

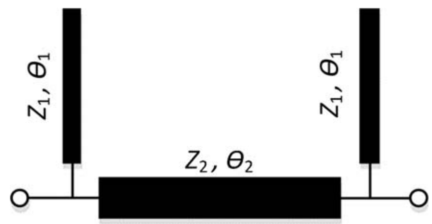

FIGURE 4 The structure of the implemented π-type dual-band J-inverter

realization of a TL with a high characteristic impedance can be solved by applying DGS under a conventional TL.[10]

In this article, the filter was designed for WLAN frequency bands with a frequency ratio $\alpha = 2.16$, the rectangular shaped DGS patterns are suitable to implement high characteristic impedance open-stubs for dual-band *J*-inverters. The calculation method for the characteristic impedance of the DGS TL is well described in Ref. [10].

3 | SIMULATION AND MEASUREMENT RESULTS

The proposed design method is experimentally validated by designing, simulating, and measuring the dual-band bandpass filter operating at 2.4 GHz and 5.2 GHz with 3-dB FBWs of $\Delta_1=\Delta_2=30\%$. The circuit is fabricated on a RT/Duroid-5880 substrate with a dielectric constant (ε_r) of 2.2 and thickness (h) of 31 mils. The second order Chebyshev type with the passband ripple of 0.01 dB is applied to the design filter, with low-pass prototype element values given as $g_0 = 1$, $g_1 = 0.4488$, $g_2 = 0.4077$, and $g_3 = 1.1007$, respectively.

Setting $Z_{CRLH} = Z_{RH} = Z_{LH} = 26.25\ \Omega$ for a given filter specification, the total electrical length of the RH TLs ($2\theta_{RH}$) is calculated as 77.4° at f_1, which is reduced by 57.77% compared to the conventional method. Figure 6 shows the top

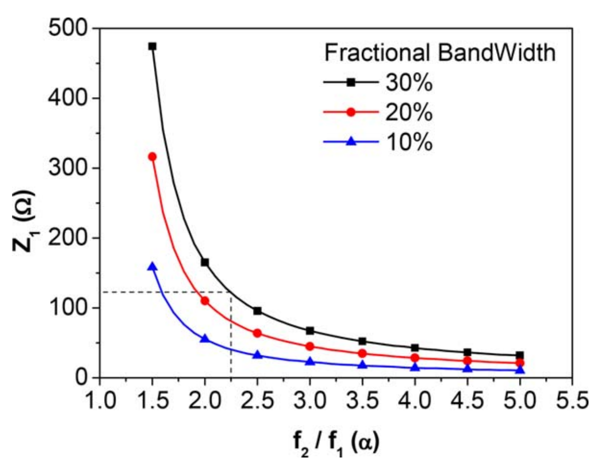

FIGURE 5 Variation in the characteristic impedance of open stub (Z_1) of dual-band J-inverter with frequency ratio (α) and 3-dB FBW. [Color figure can be viewed at wileyonlinelibrary.com]

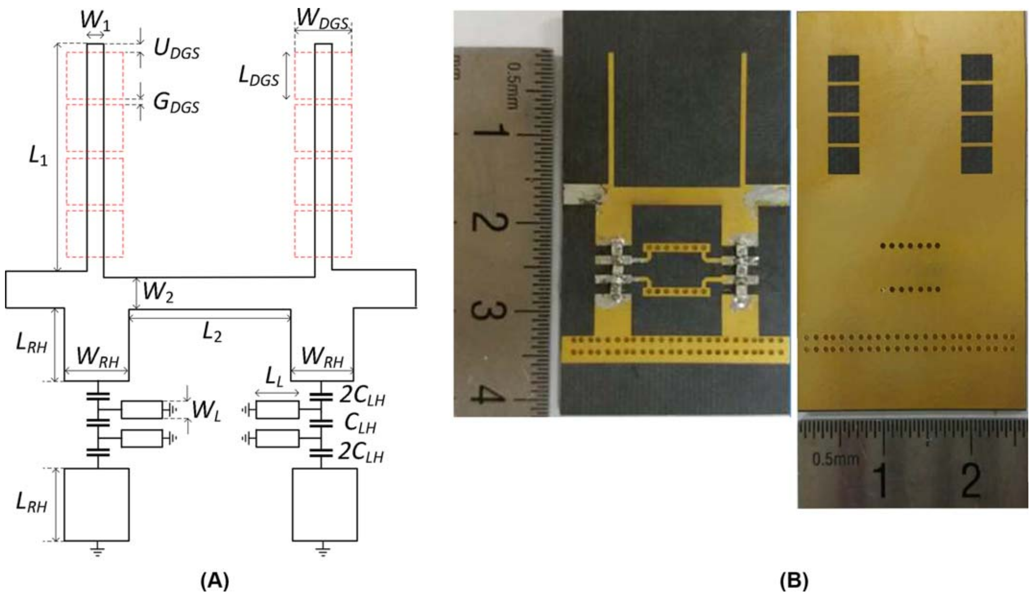

FIGURE 6 (A) The top (solid line) and bottom (dot line) view of the EM simulation layout of proposed filter and (B) the photograph of fabricated circuit. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Physical dimensions of the proposed dual-wideband bandpass filter (Unit mm)

$W_1 = 0.6$	$L_1 = 15$	$W_L = 0.5$	$L_1 = 2.5$	$W_{RH} = 4.2$	$L_{RH} = 4.7$
$W_2 = 2.05$	$L_1 = 10.4$	$W_{DGS} = 3.6$	$L_{DGS} = 3.1$	$G_{DGS} = 0.8$	$U_{DGS} = 0.6$

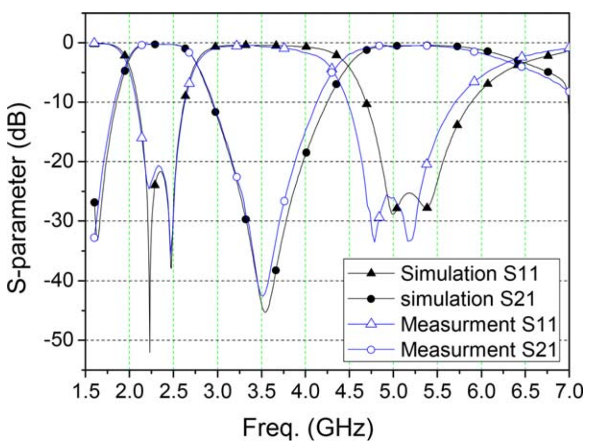

FIGURE 7 EM simulation and measurement results. [Color figure can be viewed at wileyonlinelibrary.com]

(solid line) and bottom (dot line) views of the EM simulation layout and a photograph of the fabricated filter. The simulation was performed using the HFSS of Ansoft. The lumped element values of the LH-part are given as $L_{LH} = 1.2$ nH and $C_{LH} = 1.7$ pF. In this work, the inductor (L_{LH}) is implemented as a short stub with a high impedance, and the open stubs line with $Z_1 = 136.2\ \Omega$ of the dual-band J-inverters is realized with rectangular DGSs under open stubs. Due to DGS, the physical length of the open stubs decreases by 1.99 mm, and the width of the lines increases by 0.33 mm, which makes the implementation easier under the same conditions. The physical dimensions of the designed filter are summarized in Table 1.

Figure 7 shows the EM simulation and results of the measurement for the designed dual-band bandpass filter. As seen from the figure, the results are in good agreement with those obtained from the simulation. A return loss larger than 20.65 dB and an insertion loss of less than 0.21 dB with FBW of 33.75% are obtained at the first passband center frequency of 2.4 GHz. Similarly, the measured return loss, insertion loss, and FBW at the second passband center frequency of 5.2 GHz are given as 25.6 dB, 0.5 dB, and 38.46%, respectively. The stop band attenuation between the

TABLE 2 Simulation and measurement results

	Simulation			Measurement		
Center freq. (GHz)	**S_{11} (dB)**	**S_{21} (dB)**	**3-Db FBW (%)**	**S_{11} (dB)**	**S_{21} (dB)**	**3-dB FBW (%)**
2.4	−23.40	−0.28	32.04	−23.50	−0.21	33.75
5.2	−25.33	−0.47	38.42	−33.25	−0.5	38.46

TABLE 3 Performance comparison of the proposed circuit to this in previous works

References	Substrate H (mm)/ε_r	Dual center freq. (GHz)	Return loss (dB)	Insertion loss (dB)	3-dB FBW (%)	Circuit size (mm × mm)
Ref. [4]	½.65	2.45/5.49	15/24.3	1.3/0.96	4.5/15.8	11.6 × 9.03
Ref. [5]	0.8/4.5	1.8/2.4	>15	1.38/1.34	8.3/12.9	40 × 40
Ref. [7]	0.54/2.54	5.8/10.02	18.2/14.3	1.7/1.62	11/13	36.3 × 41.6
Ref. [8]	0.787/2.2	2.4/5.2	18.14/21.46	0.28/0.46	50.24/20.2	15.3 × 48.5
This work	0.787/2.2	2.4/5.2	23.5/33.2	0.21/0.5	33.8/38.4	18.8 × 35.2

2 passbands is larger than 15 dB from 3 to 4 GHz. The results from the simulation and measurement are summarized in Table 2, and a comparison of the performance of the proposed circuit to those in previous works is shown in Table 3.

4 | CONCLUSION

This work presents a size reduction method for a composite right/left-handed (CRLH) transmission line by appropriately choosing the phase response. By using the proposed design method, the size of CRLH can be reduced about 42.8% to 71.4% depending on the frequency ratios of 2 passbands.

A demonstration is carried out by designing a dual-wideband bandpass filter using the dual-band characteristics of the composite right/left-handed transmission lines. The coupling between the 2 CRLH resonators is implemented using a dual-band J-inverter and transmission line with a high characteristic impedance of the open stubs of dual-band J-inverters is implemented using defected ground structures. Compared to a conventional CRLH dual-band filter, the physical length of the CRLH resonators is reduced by 57.77% by choosing the response of ϕ and $-\phi$. The results of the simulation and the measurements show that the designed dual-band bandpass filter has a wide dual passband and low insertion losses. Therefore, this filter is expected to be suitable for WLAN applications.

REFERENCES

[1] Hung CY, Yang RY, Lin YL. A simple method to design a compact and high performance dual-band bandpass filter for GSM and WLAN. *Prog Electromagn Res C.* 2010;13:187–193.

[2] Guan X, Ma Z, Chai P, Kobayashi Y, Anada T, Hagiwara G. Synthesis of dual-band bandpass filter using successive frequency transformations and circuit conversions. *IEEE Microw Wireless Compon Lett.* 2006;16:110–112.

[3] Wu GL, Mu W, Dai XW, Jia YC. Design of novel dual-band bandpass filter with microstrip meander-loop resonator and CSRR DGS. *Prog Electromagn Res Lett.* 2008;78:17–24.

[4] Xiao JK, Huang HF. Compact and high performance dual-band bandpass filter using resonator-embedded scheme for WLANs. *Radioengineering.* 2012;21:1050–1053.

[5] Liu H, Zhao Y, Shi L, Luo H. Dual-mode dual-band bandpass filter design using open-loop resonators. *Microw Opt Tech Lett.* 2012;54:2370–2372.

[6] Wang Q, Lim J, Jeong Y. Design of a compact dual-band branch line coupler using composite right/left-handed transmission lines. *Electron Lett.* 2016;52:630–631.

[7] Yoon K-C, Lee H-W, Lee J-C, Kim S-C. A dual-band narrow band-pass filter with half-wavelength open stubs using the CRLH metamaterial. *Microw Opt Tech Lett.* 2013;55:1887–1890.

[8] Chaudhary G, Jeong Y, Lim J. A broad-bandwidth dual-band bandpass filter design using composite right/left handed transmission lines. *Prog Electromagn Res.* 2011;25:2138–2147.

[9] Caloz C, Itoh T. *Electromagnetic Metamaterials: Transmission Lines Theory and Microwave Applications*. Wiley, Hoboken, NJ, 2006.

[10] Lim J, Lee J, Lee J, Han S, Ahn D, Jeong Y. A new calculation method for the characteristic impedance of transmission lines with modified ground structures or perturbation. *Prog Electromagn Res.* 2010;106:147–162.

How to cite this article: An B, Chaudhary G, Jeong Y. Size reduction of composite right/left handed transmission line and its application to the design of dual-band bandpass filter. *Microw Opt Technol Lett.* 2017;59:2272–2276. https://doi.org/10.1002/mop.30724

Received: 24 February 2017

DOI: 10.1002/mop.30720

Miniaturized patch antenna using a circular spiral-based metamaterial

H. Kavousi[1] | **J. Rashed-Mohassel**[1] | **M. Edalatipour**[2]

[1] School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran, Iran