Progress In Electromagnetics Research C, Vol. 10, 75–86, 2009

LOADED COUPLED TRANSMISSION LINE APPROACH OF LEFT-HANDED (LH) STRUCTURES AND REALIZATION OF A HIGHLY COMPACT DUAL-BAND BRANCH-LINE COUPLER

M. Hayati

Faculty of Engineering
Department of Electrical Engineering
Razi University
Kermanshah, Iran

M. Nosrati

Faculty of Engineering
Department of Electrical Engineering
Ilam Azad University
Ilam, Iran

Abstract—A novel approach of left-handed (LH) structures is introduced to reduce the size of microwave components by combining a loaded coupled transmission lines and complementary split ring resonators (CSRRs). The equivalent circuit of the loaded part of the proposed model is equal by that of two cascaded unit elements, thus, their performances can be equal for the same frequency range. The equivalent circuit model and subsequently, the left and right handed transmission frequencies of the proposed structure are presented. A highly miniaturized dual-band branch-line coupler (BLC) is analyzed, designed, tested and proposed by this technique. The size reduction is reported about 75% in analogy with the conventional ones. The measurement results are in good agreement with the theoretical ones.

1. INTRODUCTION

Recently left-handed (LH) materials have been widely reported by some of the authors as a highly important technique for the design of microwave components, particularly, in multi-band applications. The use of split ring resonators (SRRs) was first introduced in [1] and [2].

Corresponding author: M. Hayati (hayati@razi.ac.ir).

Combined with series capacitive gaps, these resonators have been also proposed to the design of band-pass structures [3, 4]. In [5], a low-pass filter has been realized by cascading multi CSRR cells to obtain three controllable transmission zeroes as well.

Other methods based on the theory of transmission lines have been recently introduced to make use of left-handed materials. The use of the interdigital capacitors and short-circuit stub inductors is reported in [6, 7], and the use of surface-mount-technology (SMT) lumped elements (LEs) is reported in [8].

The composite LH and RH transmission lines (TLs) technique has been proposed in [9, 10] to realize dual-band branch-line and rat-race couplers. A dual-band coupler has been also designed in [11] by using the combination of strip-shaped CSRRs and series capacitance. In some investigations, other methods have been proposed [12, 14].

In these works, it has been shown that LH TLs are useful in the design of arbitrary dual-band microwave elements due to reducing the number of circuit components in wireless systems.

The dual-band performance is the most important advantage of these works. However, it is observed that they still have a relatively large area. For example, the proposed 900/1800 MHz dual-band branch-line coupler in [9] has the size of 81.8×71.3 mm, and the other in [11] has the size of 56×54.5 mm.

While the loaded lines method is a popular approach to reduce the size of transmission line circuits [15, 17], to date, it has not been widely observed to make use of this method combined with left-handed materials.

The use of connecting lines as a cascade two unit elements instead of the internal series stubs is useful to increase bandwidth in digital elliptic filters [15]. In this study, a compact branch-line coupler has been recently introduced by this technique.

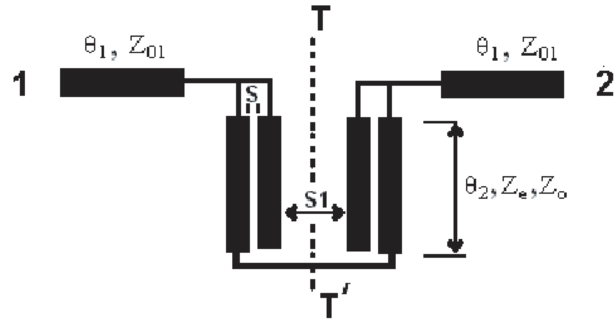
In this paper, a novel method to design a dual-band coupler accompanied by further size reduction is proposed in which a combination of four coupled loaded transmission lines and complementary split ring resonators (CSRRs) leads to providing the positive and negative phase responses and to the design of a dual-band coupler accompanied by high size reduction.

The novel compact dual-band BLC is designed at 0.644/1.66 GHz and fabricated on a 30-mil-thick substrate with a relative dielectric constant $\varepsilon_r = 3.5$. Furthermore, the simulated and measured results of the proposed dual-band BLC are presented.

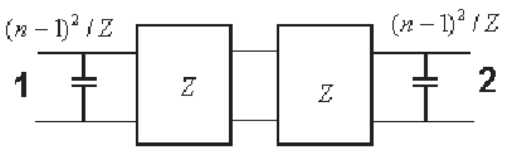
Compared with the conventional dual-band BLC in [9] and [11], the size reduction is reported about 75% and 52% respectively with a comparable performance.

2. THE LOADED COUPLED TRANSMISSION LINES

To reduce the area of the proposed BLC accompanied by a dual-band performance, a loaded model of coupled lines shown in Figure 1(a) is presented. The parallel-coupled lines, with the electrical length θ_2, are considered as a load for two single lines with the electrical length θ_1. As discussed in [15, 18], the network model of this structure can be derived as shown in Figure 1(b). If the equality of this model is shown by a quarter wavelength line, used in the conventional ones, a new compact dual-band coupler can be designed using combination of this model by complementary split ring resonators.



(a)



(b)

Figure 1. (a) The loaded coupled transmission lines [15]. (b) Its equivalent network model.

Initially, to demonstrate this, the odd and even modes analysis is used. Similar to [15], the total impedance of this structure obtained from the odd mode analysis can be calculated as follows:

$$Z_{in1} = Z_{01} \frac{Z_1 + jZ_{01}\tan(\theta_1)}{Z_{01} + jZ_1\tan(\theta_1)} \tag{1}$$

where Z_1 and Z_{in1} are the input impedance of the two adjacent transmission lines with the electrical length θ_2 and the total impedance of port 1 resulted from the odd mode analysis, respectively.

Similarly, by using the even mode analysis, the impedance of the structure can be derived as follows:

$$Z_{in2} = Z_{01}\frac{Z_2 + jZ_{01}\tan(\theta_1)}{Z_{01} + jZ_2\tan(\theta_1)} \tag{2}$$

where Z_2 and Z_{in2} are the input impedance of the two adjacent transmission lines with the electrical length θ_2 and the total impedance of port 1 resulted from the even mode analysis, respectively.

To determine the basic parameters of the proposed model, it is needed to equal the Z_{in1} and Z_{in2} by the obtained impedances of a quarter wavelength line from the odd and even modes analysis respectively.

3. LH TL AND RH TL

To make a comprehensive analysis, initially, the dual-band coupler proposed in [11] is followed. Figure 2 shows its layout and equivalent circuit model. As discussed in [11] and observed in its obtained equations, by adjusting the series capacitance C_g, given in Figure 2, right-handed pass-band can be moved. However, there is a certain value to increase C_g, and in fact, this tight limitation is forced by the left-handed frequency. On the other hand, by increasing C_g, the right-handed transmission frequency can be shifted towards lower frequencies; however, if this increase is continued more than a certain value, as apposed to it, the left-handed transmission frequency shifts

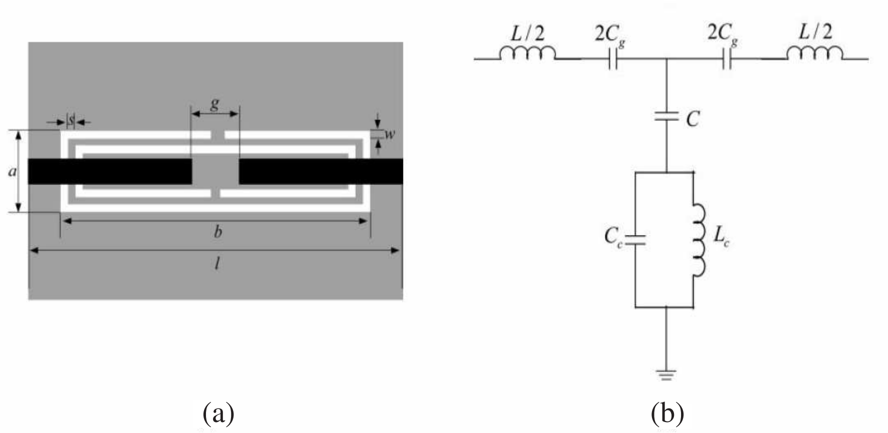
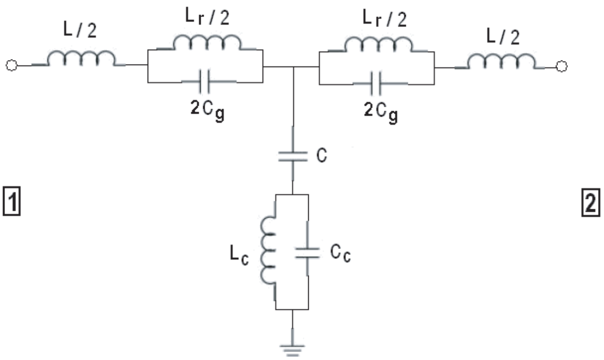


Figure 2. (a) and (b) the conventional dual-band BLC and its equivalent circuit model.

(a)



(b)

Figure 3. (a) The proposed loaded coupled transmission lines. (b) Its equivalent circuit model.

towards the higher frequencies. This phenomena can be demonstrated using full-wave simulator tools. Subsequently, this technique does not give the possibility to design a dual-band component for two certain frequencies.

Therefore, here we tried to present a new model of the loaded TLs shown in Section 2 combined with CSRRs to obviate this problem to some extent. Inspecting the structure shown in Figure 1, and as discussed in [11] and the other previous studies, by taking into account that the series impedance of the T circuit model of the LH cell (Z_S) is dominated by C_g (the series capacitance shown in Figures 2 and 3), the proposed structure therefore needs to have more coupling between the two inside open stubs to provide a stronger capacitive coupling. In fact, as shown in Figure 1, S_1 should be much smaller than S. By taking this fact into account, the layout shown in Figure 3 can be considered.

Figure 3 shows the layout of the proposed model combined with CSRRs and its lumped element equivalent circuit. As shown, the series capacitance implemented by a series gap, interdigital capacitor or short-circuit stub inductor in previous works is realized here by using two coupled lines.

As discussed in [11–13] and upon the supposition that the electrical size is small compared with the wavelength and considering the basic cell of periodical structure, the phase shift factor can be calculated as follows:

$$\cos\phi = 1 - \frac{\omega^2 C[(L+L_r) - LL_r C_g \omega^2][1 - L_c C_c \omega^2]}{2[1 - C_g L_r \omega^2][1 - \omega^2 L_c (C + C_c)]} \tag{3}$$

Left handed pass-band occurs in the frequency region as follows:

$$f_L = \frac{1}{\pi\sqrt{C(L+L_r) + 4C_g L_r + 4L_c(C+C_c)}} \tag{4}$$

$$f_H = \frac{1}{2\pi\sqrt{L_c C_c}} \tag{5}$$

Similarly, it can be shown that the right handed pass-band is found above the frequency as follows:

$$f_R = \frac{1}{2\pi}\sqrt{\frac{L_r + L}{C_g L_r L}} \tag{6}$$

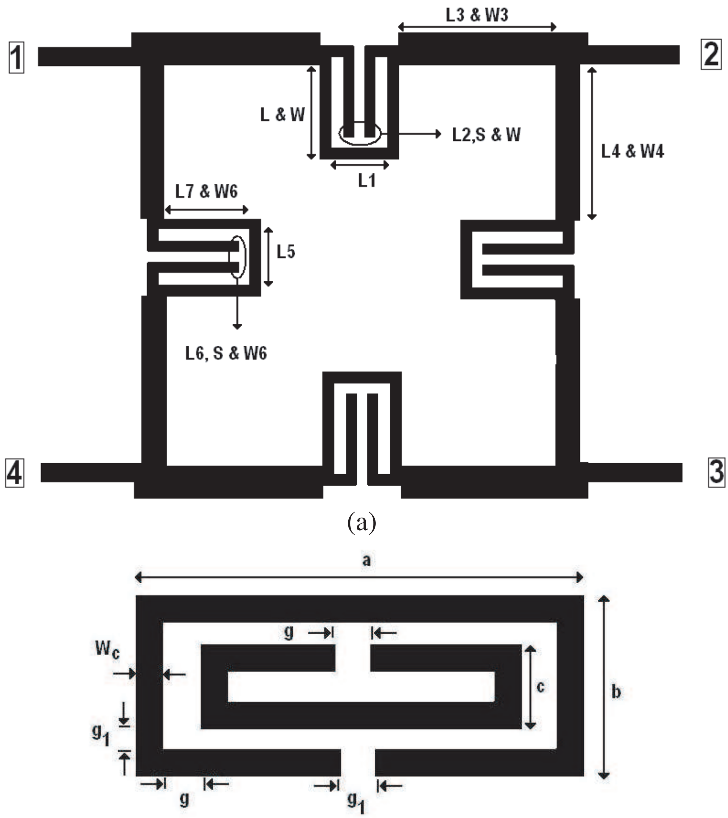
Compared left and right-handed transmission frequencies with the other studies, it is observed that in this case, the mentioned problem has been obviated. On the other hand, by increasing C_g, both f_R and f_H tend to shift towards lower frequencies, and subsequently, the size of the dual-band component can be dramatically reduced.

As discussed in [9], the phase response of the structure, at low frequencies, approaches to the left-handed transmission-line phase because the contribution of the components which provide right-handed band is negligible, and vice versa, the phase response at high frequencies approaches to the right-handed transmission-line phase.

According to (3) and as apposed to [11], in calculating (3), the term $-\omega^2$ emerges in this equation. By taking this fact into account and considering the discussion in [9] and [11], $-270°(+90°)$ phase shift at first operating frequency and $-90°$ phase shift at second frequency can be observed.

4. DUAL-BAND BRANCH-LINE COUPLER

To design a compact dual-band BLC, initially, a single-band one can be designed by using Equations (1) and (2) and using even and odd modes analysis; afterwards, by applying complementary split ring resonators, a highly compact dual-band BLC can be realized.



(b)

Figure 4. (a) Simulated layout of the proposed dual-band BLC. (b) The layout of used complementary split ring resonator (CSRR) with dimension of: $L = 9.5\,\mathrm{mm}$, $L_1 = 8.5\,\mathrm{mm}$, $L_2 = 8\,\mathrm{mm}$, $L_3 = 11\,\mathrm{mm}$, $L_4 = 12\,\mathrm{mm}$, $L_5 = 6.9\,\mathrm{mm}$, $L_6 = 9\,\mathrm{mm}$, $L_7 = 10.5\,\mathrm{mm}$, $W = 2\,\mathrm{mm}$, $W_3 = 2.91\,\mathrm{mm}$, $W_4 = 1.715\,\mathrm{mm}$, $W_6 = 1.2\,\mathrm{mm}$, $S = 1\,\mathrm{mm}$, $a = 12\,\mathrm{mm}$, $b = 6\,\mathrm{mm}$, $c = 4.4\,\mathrm{mm}$, $W_c = 0.5\,\mathrm{mm}$, $g = 0.3\,\mathrm{mm}$, $g_1 = 1.2\,\mathrm{mm}$.

At the next step, the designed coupler is simulated by full-wave electromagnetic (EM) simulation tool (ADS) with the dimensions shown in Figure 4(a).

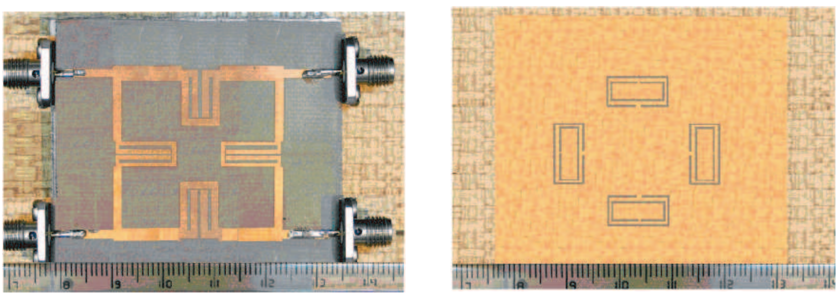
The dual-band BLC is designed to work at frequencies f_1 and f_2. The conceptual schematics and a photograph of the implemented circuit of this BLC are given in Figures 4 and 5, respectively.

To have a simple design, all of the CSRRs are implemented with the same dimensions given in Figure 4(b).

The scattering parameters of the BLC simulated by a full-wave electromagnetic (EM) simulation tool (ADS) and measured by an Agilent 8722ES network analyzer over the frequency range from 0.2 to 2 GHz are given in Figures 6 and 7. The simulated and measured results are in good agreement in general, except at 2 GHz frequency.

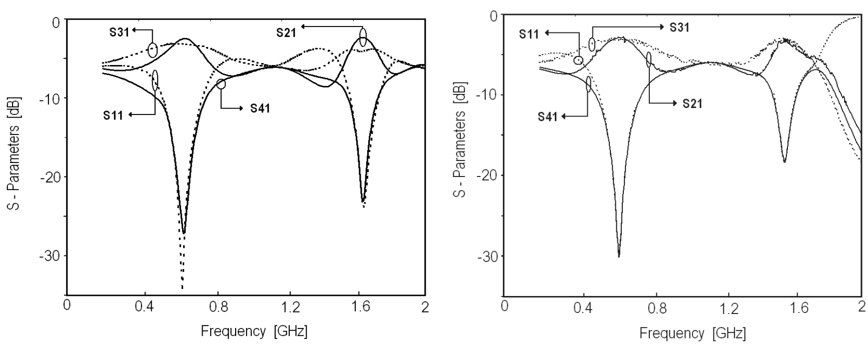
The two operating frequencies are chosen as $f_1 = 644$ MHz and $f_2 = 1660$ MHz. It is obvious that by having these frequencies close to lower frequencies than those of the GSM system, it gives the possibility to have more size reduction. It is necessary to state that it is possible to achieve a dual-band BLC at any arbitrary pair of frequencies with this approach. In fact, the loaded coupled transmission lines and CSRRs can be tuned to change the right-hand and left-hand transmission frequencies, respectively.

As observed from Figure 7, the phase difference at first frequency is $-270°(+90°)$ and at second frequency is $-90°$. The performances in



(a) (b)

Figure 5. Photographs of the proposed dual-band BLC: (a) top face; (b) bottom face.



(a) (b)

Figure 6. (a) The simulated and (b) measured S-parameters of the proposed dual-band BLC.

both pass-bands are summarized in Tables 1 and 2.

As given in these tables, in the measurement, f_1 is shifted to 640 MHz, and f_2 is shifted to 1570 MHz.

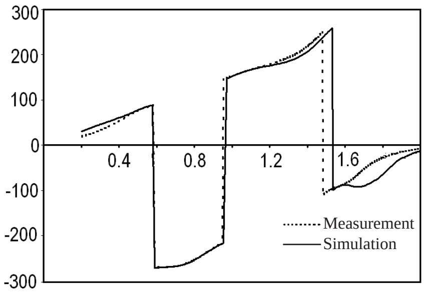


Figure 7. Phase difference between S_{21} and S_{31} in the dual-band BLC.

Table 1. Performance of the proposed Dual-band BLC at the first operating frequency.

	Simulation	Measurement
Operation frequency (f_1)	644 MHz	640 MHz
Return Loss (S_{11})	–34.4 dB	–29.4 MHz
Isolation (S_{41})	–27.1 dB	–30.2 dB
Output 1 (S_{21})	–2.52 dB	–3.22 dB
Output 2 (S_{31})	–3.13 dB	–3.61 dB
Phase Difference	–270.8° (89.2°)	–268.87° (91.13°)
$BW_{1\ dB}$	88 MHz (13.6%)	86 MHz (13.4%)

Table 2. Performance of the proposed Dual-band BLC at the second operating frequency.

	Simulation	Measurement
Operation frequency (f_2)	1660 MHz	1570 MHz
Return Loss (S_{11})	–23.8 dB	–18.4 dB
Isolation (S_{41})	–22.9 dB	–18.22 dB
Output 1 (S_{21})	–2.37 dB	–3.43 dB
Output 2 (S_{31})	–4.07 dB	–3.13 dB
Phase Difference	–90.3°	–92°
BW_{1dB}	60 MHz (3.61%)	41 MHz (2.61%)

5. CONCLUSION

A novel dual-band BLC based on loaded coupled transmission lines and complementary split ring resonators (CSRRs) with an extremely compact microstrip structure, low fabricated cost, a size reduction more than that of previous works has been realized. It has been demonstrated that the new BLC works as well as the conventional ones, though with a size reduction about 75% and 52% compared with [9] and [11], respectively.

The main drawback in this design is that the bandwidth is very wide at the first band, and it is very narrow at the second band as compared to conventional ones.

ACKNOWLEDGMENT

The authors would like to thank R. Khosravi, Iran Telecommunication Center, for his helpful assistance.

REFERENCES

1. Baena, J. D., J. Bonache, F. Martin, R. Marques, F. Falcone, T. Lopetegi, M. A. G. Laso, J. Garcia, I. Gil, M. F. Portillo, and M. Sorolla, "Equivalent-circuit models for split-ring resonators and complementary split ring resonators coupled to planar transmission lines," *IEEE Trans. Microwave Theory Tech.*, Vol. 53, 1451–1461, 2005.
2. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index refraction," *Science*, Vol. 292, 77–79, Apr. 2001.
3. Mondal, P., M. K. Mandal, A. Chaktabary, and S. Sanyal, "Compact bandpass filters with wide controllable fractional bandwidth," *IEEE Microwave Wireless Comp. Lett.*, Vol. 16, 540–542, 2006.
4. Bahrami, H., M. Hakkak, and A. Pirhadi, "Analysis and design of highly compact bandpass waveguide filter utilizing complementary split ring resonators (CSRR)," *Progress In Electromagnetics Research*, PIER 80, 107–122, 2008.
5. Zhang, J., B. Cui, S. Lin, and X.-W. Sun, "Sharp-rejection low-pass filter with controllable transmission zero using complementary split ring resonators (CSRRs)," *Progress In Electromagnetics Research*, PIER 69, 219–226, 2007.

6. Caloz, C. and T. Itoh, "Novel microwave devices and structures based on the transmission line approach of meta-materials," *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 1, 195–198, 2003.
7. Caloz, C. and T. Itoh, "Application of the transmission line theory of left-handed (LH) materials to the realization of a microstrip LH transmission lines," *IEEE AP-S Int. Symp. Dig.*, Vol. 2, 412–415, 2002.
8. Iyer, K. and G. V. Eleftheriades, "Negative refractive-index meta-materials supporting 2-D waves," *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 2, 1067–1070, 2002.
9. Lin, I. H., M. D. Vincentis, C. Caloz, and T. Itoh, "Arbitrary dual-band components using composite right/left-handed transmission lines," *IEEE Trans. Microwave Theory Tech.*, Vol. 52, 1142–1149, Apr. 2004.
10. Sanda, A., C. Caloz, and T. Itoh, "Characteristics of the composite right/left-handed transmission lines," *IEEE Microwave Wireless Comp. Lett.*, Vol. 14, 68–70, Feb. 2004.
11. Niu, J.-X. and X.-L. Zhou, "A novel dual-band branch line coupler based on strip-shaped complementary split ring resonators," *Microwave and Opt. Tech. Lett.*, Vol. 49, No. 11, 2859–2862, Nov. 2007.
12. Siso, G., J. Bonache, M. Gill, I. Gill, J. Garcia-Garcia, and F. Martin, "Compact rat-race hybrid based on complementary split rings resonators," *PIERS Online*, Vol. 3, No. 3, 2007.
13. Smith, D. R., W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, Vol. 84, No. 18, 4184–4187, May 2000.
14. Monti, G. and L. Tarricone, "Dual-band artificial transmission lines branch-line coupler," *International Journal of RF and Microwave Computer-aided Eng.*, 53–62, Sept. 2007.
15. Nosrati, M. and S. K. Valashani, "A novel compact branch-line coupler using four coupled transmission lines," *Microwave and Opt. Tech. Lett.*, Vol. 50, No. 6, 1712–1714, June 2008.
16. Nosrati, M. and A. Najafi, "Bandwidth enhancement and further size reduction of a class of elliptic-function low-pass filter using modified hairpin resonators," *Progress In Electromagnetics Research C*, Vol. 5, 187–194, 2008.
17. Chan, Y.-H. and J.-S. Hong, "Compact wide-band branch-line hybrids," *IEEE Trans. Microwave Theory Tech.*, Vol. 54, 704–709, Apr. 2006.

18. Malherbe, J. A. G., *Microwave Transmission Line Filters*, Artech House, Inc., 1979.