Progress In Electromagnetics Research Letters, Vol. 40, 153–162, 2013

MINIATURIZED HYBRID BRANCH LINE COUPLERS BASED ON A SQUARE-SPLIT RESONATOR LOADING TECHNIQUE

Lamia Al-Khateeb[*]

Department of Communications Engineering, Hijjawi Faculty of Engineering Technology, Yarmouk University, Irbid, Jordan

Abstract—In this paper, new miniaturized hybrid branch line couplers loaded by square-split ring resonators are proposed. This loading technique increases the electrical length of transmission lines by patterning the ground plane under the conductor trace in microstrip lines with the complementary, dual-behavior, configuration of square-split ring resonators. Each branch is loaded by one resonator in the first coupler and by two resonators in the second coupler. Hence, compact sizes of 9.29 mm × 9.57 mm, and 8.88 mm × 9.11 mm, or equivalently $0.2\lambda_g \times 0.2\lambda_g$ and $0.19\lambda_g \times 0.19\lambda_g$, respectively, are obtained at the operation frequency, 2.4 GHz. This corresponds to 66.14% and 60.18% of a conventional structure's area, respectively. Moreover, the new designs can suppress higher harmonic components due to the bandstop response of the square-split resonators at their resonant frequency while maintaining similar measured performance compared to the conventional branch-line hybrid coupler. Measured and simulated responses are in very good agreement which validates the proposed structures and technique. This technique can also be applied to minimize the size of other microwave circuits.

1. INTRODUCTION

Recent years witnessed the emergence of metamaterials [1]. Metamaterials are synthesized materials in which electron oscillations over electrically small inclusions can result in new electromagnetic properties [1]. There are two main approaches for metamaterial design at microwave (MW) frequencies: the resonance-type approach and the artificial transmission line (TL) approach [2, 3].

Received 11 April 2013, Accepted 14 May 2013, Scheduled 29 May 2013

[*] Corresponding author: Lamia Al-Khateeb (lamiaalkhateeb@yahoo.com).

The resonance-type is based on loading the host transmission lines by artificial magnetic materials (AMMs), such as split ring resonators (SRRs) [1]. Etching an AMM on a host transmission line generates a high magnetic coupling between them. As a result, a stopband appears in the vicinity of the AMM's resonance frequency. This stopband can be interpreted as a consequence of the new properties of the AMM which behaves as a negative effective permeability medium in a narrow band around the resonance. To reduce the size of AMM-based structures, it is necessary to decrease the electrical size of the AMMs. However, in practice, due to the limited lateral resolution of standard fabrication systems, it is difficult to drive AMM dimensions below one-tenth of a wavelength at resonance, and hence, alternative AMMs with extra compact topologies should be considered. Moreover, challenges remain in proposing accurate equivalent circuit models for these AMMs to produce more systematic synthesis methods for AMM-based MW circuits [2, 4].

Many artificial magnetic material inclusions are introduce in the literature. However, most of these inclusions have the same functionality as for split ring resonators. In [4] a square split ring resonator (S-SRR) was proposed which has more degrees in freedom from design point of view and more magnetic coupling with the host transmission line than SRR. Saha et al. build a theoretical model for S-SRRs to estimate their resonance frequency and their magnetic polarizability in [4], besides that, they investigate the bandstop behavior of these resonators when loaded into coplanar waveguide transmission lines.

A dual counterpart of SRR, called complementary SRR (CSRR), exhibits negative permittivity was first introduced in [5]. A transmission line loaded by this resonator synthesizes a delay line, i.e., the electrical length of a fixed-length TL effectively increases by etching the CSRRs on its ground plane [6]. Hence, it is useful to use this kind of TLs in microwave circuits to get size reduction [6].

Different techniques have been investigated and used in order to produce compact branch-line couplers by decreasing the physical lengths of their branches compared to conventional structures [7–11]. This paper introduces a new technique to produce two miniature hybrid branch line couplers (HBLCs) operate at 2.4 GHz by loaded the complementary shape S-SRRs into the ground plane of the microstrip transmission lines used to implement each branch. The square shape is chosen because of its advantages over conventional SRR as mentioned before.

By means of this newly proposed technique, miniaturized microstrip branch-line couplers are produced. Their occupied size is between 60.18%–66.14% of that of a conventional one. Each branch in the first coupler is loaded by one S-SRR. Whereas two resonators per branch are loaded into the second coupler. It can be noticed that increasing the number of resonators per branch increases the compactness factor in the coupler compared to conventional structures. This loading technique can be applied to other microwave circuits.

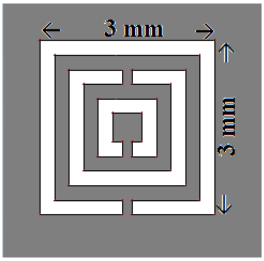
2. RESONATOR DESIGN AND RESPONSE

In order to load each branch of the proposed HBLCs with suitable S-SRRs. The resonance frequency of these resonators at which a bandstop response can be detected, should be far from the passband region of the HBLCs. This condition can be achieved by properly choose the dimensions of the resonators.

To demonstrate the performance of the S-SRR, a one-period, complementary S-SRR etched on the ground plane of a microstrip transmission line has been designed as shown in Figure 1. The substrate used for this structure is RT/Duroid 6010LM which has a dielectric constant of 10.2, loss tangent of 0.0023, and a thickness of 0.635 mm. The designed resonance frequency of the resonator is chosen to be 4.8 GHz. This resonance frequency is given by [12]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{2}{\pi r_0 L C_{\mathrm{pul}}}} \tag{1}$$

where C_{pul} is the per unit length (p.u.l.) capacitance between the square loops, L the total inductance of the S-SRR, and r_0 the average radius of the three square loops. Using the design equations introduced in [4], the dimensions of the three concentric squares which represent the square resonator as shown in Figure 1 can be calculated.



All lines and spacings widths within the S-SRR = 0.25 mm

Figure 1. Layout of the complementary S-SRRs patterned in the ground plane of a microstrip transmission line.

The resonance frequency is chosen to be twice the center passband frequency of the proposed HBLCs for two reasons. Firstly, to insure that the passband of the HBLCs will not be affected by the stopband of the S-SRRs. Secondly, to suppress higher-order harmonics from the responses of the new couplers [13]. It has been noticed that increasing the number of the concentric loops within the S-SRR increases the induced magnetic flux inside the loops, and hence, increases the effective electrical length of the loaded TLs.

Figure 2 shows the simulated scattering parameters of the S-SRR. The full-wave electromagnetic simulator, IE3D, which is based on the method of moments is used to build the design [14]. The simulated resonance frequency appears at 4.77 GHz which is very close to the theoretical value. The small difference between the simulated and the theoretical values can be referred to the parasitic discontinuities effects [15]. For example, there are parasitic capacitances associated with the four corners in the square geometry because of the additional charge accumulation due to the field concentration [15]. However, these discontinuities have a negligible effect on the total performance of the resonator, and hence, an insignificant shift in the resonance frequency appears.

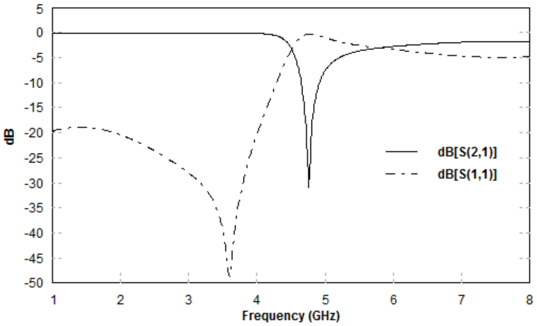


Figure 2. The simulated scattering parameters of the complementary S-SRRs loaded into the ground plan of microstrip TL.

Table 1 summarizes the simulated characteristics of the proposed AMM. The S-SRR demonstrates high insertion loss (> 20 dB), and high attenuation rates near the resonance frequency (> 200 dB/GHz).

The equivalent-circuit model for the S-SRR loaded transmission line is shown in Figure 3(a). L and C are the per-section inductance and capacitance of the transmission line which can be determined from a transmission-line calculator, while the S-SRR is modeled as a resonant tank (with inductance L_s and capacitance C_s) magnetically

Table 1. Performance of the square-split ring resonator.

Parameter	Simulation
Resonance frequency	4.77 GHz
Return loss	0.34 dB
Insertion loss	30.52 dB
Q-factor	3.68
Attenuation rate near the resonance	210.42 dB/GHz

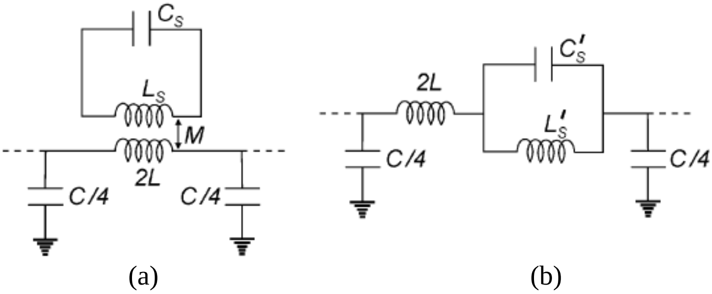


Figure 3. (a) Lumped-element equivalent circuit model for the basic cell of the S-SRR loaded transmission line. (b) Simplified circuit model.

coupled to the line through a mutual inductance, M [16].

A simplified model of the S-SRR load transmission line is shown in Figure 3(b). From this model the dispersion relation can be obtained as follows [2]:

$$\cos(\beta l) = 1 - \frac{LC\omega^2}{2} + \frac{\frac{C}{C_s'}}{4\left(1 - \frac{\omega_0^2}{\omega^2}\right)} \tag{2}$$

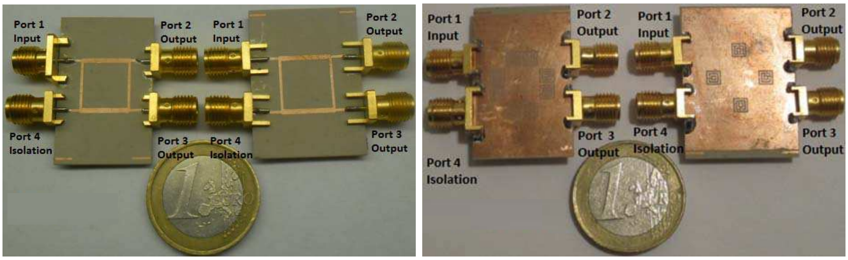
with $C_s' = L_s/(M^2\omega_0^2)$, $L_s' = C_s M^2 \omega_0^2$, and $\omega_0^2 = 1/(L_s C_s)$. β is the propagation constant and l the period of the structure [2]. L_s, C_s and M can be determined using the SRR circuit model proposed in [2].

The dispersion relation in (2) can be used to show that the new loaded transmission line exhibits an effective larger electrical length compared to a conventional transmission line having the same physical length at frequencies below the S-SRR's resonant frequency. Hence, reducing the physical length in the loaded transmission line will compensate this effect.

3. COMPACT HYBRID BRANCH LINE COUPLERS (HBLCS)

In this section new compact HBLCs are proposed, where each of their branches are loaded by one or two complimentary S-SRRs resonators. Their resonance frequency, 4.77 GHz, for the two aforementioned reasons. The electrical length of each branch can be tuned by changing the number of the loading resonators and the separation between them in case there are more than two resonators per branch. This separation determines the magnetic and electric coupling between the adjacent resonators which gives us more design flexibility in controlling the reduction factor. It can be shown that the more resonators loaded on each branch, the more increment in the electrical length is obtained, and hence, the more size reduction can be achieved.

A photograph of the implemented HBLCs loaded by one resonator per branch and two resonators per branch are shown in Figure 4, with port orientation indicated as well. The operating frequency is chosen as 2.4 GHz which is suitable for Wi-Fi applications. Both circuits are fabricated on Duroid 6010 substrates with a dielectric constant of 10.2 and a thickness of 0.635 mm. The four-port HBLCs are measured with a network analyzer and a calibration kit is used to calibrate the system to the SMA connectors.



(a) (b)

Figure 4. Photograph of the fabricated HBLCs loaded by two (left side of each figure) and one (right side of each figure) resonators in each branch. (a) Top view. (b) Bottom view.

The measured scattering parameters are shown in Figure 5, and the measured performance parameters for both circuits are summarized in Table 2. In the two circuits the phase differences between S_{21} and S_{31} is close to 90°. Quadrature phase differences are obtained with errors less than 1° at 2.4 GHz and the amplitude imbalance between

Table 2. Performance of the proposed HBLCs (measured response).

Loading per branch	One resonator	Two resonators
Operating Frequency	2.41 GHz	2.40 GHz
Return loss	15.37 dB	19.29 dB
Isolation	16.12 dB	17.22 dB
Output 1	−3.59 dB	−3.47 dB
Output 2	−3.52 dB	−3.31 dB
Amplitude Imbalance	0.16 dB	0.18 dB
Outputs phase Difference	0.09	0.07
Reduction ratio compare to a conventional HBLC	33.86%	39.82%

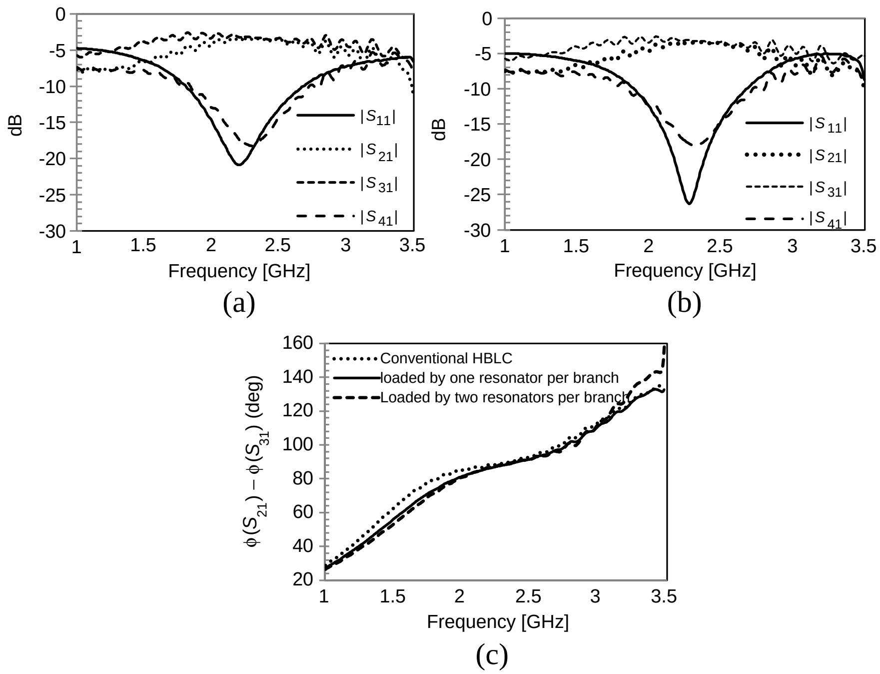
S_{21} and S_{31} is less than 0.2 dB in both passbands, which means that the incident power is evenly divided between the output ports. The isolation/return losses are larger than 15 dB in the two circuits.

The size reduction factors for the new HBLCs compared to that of a conventional HBLC equal 33.86% for the coupler with one resonator loading, and 39.82% for the coupler with two resonators loading.

Table 3 summarizes the recently published branch-line hybrid couplers with reduced wavelength in transmission line and this work. A significant improvement in size reduction in addition to the ability to suppress higher-order harmonics is obtained using the proposed technique.

Table 3. Comparisons of the major features of various hybrid branch-line couplers.

Reference	Relative area	Frequency (GHz)	Harmonic suppression	Type
Conventional	100%	2.4	No	
[7]	63.1%	1.8	No	ATLs
[8]	77%	3.5	No	PBG
[9]	63%	2.4	Yes	Shunt stubs
[10]	64%	2.2	No	SBO
[11]	38%	3.45	No	Discontinuities
This work	60.18%	2.4	Yes	S-SRR



(a) (b) (c)

Figure 5. Measured responses for the proposed HBLCs shown in Figure 4. (a) Measured S-parameters of the HBLC loaded by one resonator per branch. (b) Measured S-parameters of the HBLC loaded by two resonators per branch. (c) Measured output phase differences in the loaded HBLCs as compared to a conventional HBLC.

4. CONCLUSIONS

A miniaturization technique based on increasing the electrical length of transmission lines has been proposed. This technique is achieved by simply loading microstrip transmission lines with the complimentary square split ring resonators on the ground plane below the center conductor. Two compact hybrid branch line couplers are designed based on this technique. The first coupler is loaded by one resonator per branch and has a reduction factor of 33.86%. Whereas the second coupler is loaded by two resonators per branch and has a reduction factor of 39.82% compared to conventional coupler. Measured results for the two couplers show excellent responses.

REFERENCES

1. Pendry, J. B., A. J. Holden, D. J. Ribbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, 2075–2084, Nov. 1999.
2. Baena, J. D., J. Bonache, F. Martin, R. Marques, F. Falcone, T. Lopetegi, M. A. G. Laso, J. Garcia, I. Gil, 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, No. 4, 1451–1461, Apr. 2005.
3. Caloz, C., H. Okabe, H. Iwai, and T. Itoh, "Transmission line approach of left-handed metamaterials," *USNC/URSI National Science Meeting*, San Antonio, TX, Jun. 16–21, 2002.
4. Saha, C., J. Y. Siddiqui, and Y. M. M. Antar, "Square split ring resonator backed coplanar waveguide for filter applications," *2011 XXXth URSI General Assembly and Scientific Symposium*, 1–4, Aug. 13–20, 2011.
5. Falcone, F., T. Lopetegi, J. D. Baena, R. Marqués, F. Martín, and M. Sorolla, "Effective negative-ε stopband microstrip lines based on complementary split ring resonators," *IEEE Microw. Wireless Compon. Lett.*, Vol. 14, No. 6, 280–282, Jun. 2004.
6. Pasakawee, S. and Z. Hu, "Left-handed microstrip delay line implemented by complementary split ring resonators (CSRRs)," *Asia Pacific Microwave Conference 2009*, 599–601, Singapore, 2009.
7. Eccleston, K. W. and S. H. M. Ong, "Compact planar microstripline branch-line and rat-race couplers," *IEEE Trans. Microwave Theory Tech.*, Vol. 51, No. 10, 2119–2125, Oct. 2003.
8. Shum, K. M., Q. Xue, and C. H. Chan, "A novel microstrip ring hybrid incorporating a PBG cell," *IEEE Microw. Wireless Compon. Lett.*, Vol. 11, No. 6, 258–260, Jun. 2001.
9. Mondal, P. and A. Chakrabarty, "Design of miniaturised branch-line and rat-race hybrid couplers with harmonics suppression," *IET Microwaves, Antennas & Propagation*, Vol. 3, No. 1, 109–116, Feb. 2009.
10. Bekasiewicz, A., P. Kurgan, and M. Kitlinski, "New approach to a fast and accurate design of microwave circuits with complex topologies," *IET Microwaves, Antennas & Propagation*, Vol. 6, No. 14, 1616–1622, Nov. 2012.
11. Jung, S.-C., R. Negra, and F. M. Ghannouchi, "A design

methodology for miniaturized 3-dB branch-line hybrid couplers using distributed capacitors printed in the inner area," *IEEE Trans. Microwave Theory Tech.*, Vol. 56, No. 12, 2950–2953, 2008.

12. Marqués, R., F. Mesa, J. Martel, and F. Medina, "Comparative analysis of edge- and broadside-coupled split ring resonators for metamaterial design — Theory and experiment," *IEEE Trans. Antennas Propag.*, Vol. 51, No. 10, 2572–2581, Oct. 2003.
13. Zhang, J. and X.-W. Sun, "Harmonic suppression of branch-line and rat-race coupler using complementary spilt ring resonators (CSRR) cell," *Progress In Electromagnetics Research Letters*, Vol. 2, 73–79, 2008.
14. Zeland Software, Inc., "IE3D simulator," Fremont, CA, 2007.
15. Simons, R. N., *Coplanar Waveguide Circuits, Components, and Systems,* John Wiley & Sons, New York, 2001.
16. Martín, F., F. Falcone, J. Bonache, R. Marqués, and M. Sorolla, "A new split ring resonator based left handed coplanar waveguide," *Appl. Phys. Lett.*, Vol. 83, 4652–4654, 2003.