Miniaturization of U-Shaped Multi-Band Metamaterial Structures

***Oznur Turkmen*[1,2], *Evren Ekmekci*[1,3], and *Gonul Turhan-Sayan*[1]**

[1]Dept. of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey
oturkmen@metu.edu.tr, ekmekci@eee.metu.edu.tr, gtsayan@metu.edu.tr

[2]Dept. of Electronics and Telecommunications Engineering, Kocaeli University, Kocaeli, Turkey

[3]Dept. of Electronics and Communication Engineering, Suleyman Demirel University, Isparta, Turkey

Abstract

In this study, transmission characteristics of single-sided and double-sided (in broadside-coupled configuration) U-shaped multiple ring resonators (UMRR) are investigated on a comparative basis for the purpose of miniaturization. Transmission spectra (i.e. $|S_{21}|$ versus frequency curves) of both single and double sided UMRR topologies are computed by CST Microwave Studio for the special cases of unit cells with single ring and double concentric rings. Although all these unit cells have exactly the same physical size, simulation results have revealed that broadside-coupled UMRR topologies provide much smaller resonance frequencies (hence considerably smaller electrical sizes) as compared to their single-sided counterparts.

1. Introduction

Metamaterials are specially designed periodic structures which can show unique properties such as negative values of permeability and/or negative values of permittivity over finite frequency bands. Theoretical aspects and various applications of metamaterials have been investigated in detail in a vast amount of publications for the last decade [1-10]. Negative values of permittivity are known to be possible by using periodic thin wire array structures depending on plasma theory [2]. Negative values of permeability on the other hand, can be obtained by using some special magnetic resonator structures [3, 5-10] including the well known split ring resonator (SRR) topology. However, these magnetic resonator structures promise negative values of permeability over narrow spectral bands. Therefore, there is a need to design multi-band metamaterial structures.

Most of the multi-band magnetic resonator topologies reported so far make use of periodic arrays of super cells which are composed of two or more different unit cells [6,11,12]. Such topologies usually have larger electrical sizes due to the increased physical size of the super cells. Electrical size of a metamaterial resonator structure, however, is an important design parameter and it should be kept as small as possible as the theory of metamaterials is based on the effective medium approach[5,8]. The U-shaped multiple ring resonator (UMRR) topology studied in this paper is constructed as a periodic array of a compact unit cell which includes concentrically printed multiple U rings. Therefore, this multi-band structure has inherently a smaller electrical size as compared to super-cell type multi-band magnetic resonators. In the present study, effects of broadside coupling to the UMRR topology are investigated for further miniaturization. Single-sided and broadside-coupled versions of the single ring and double ring UMRR arrays are simulated by using CST Microwave Studio (MWS) to compute and compare their electrical sizes.

2. Design and Simulation Setup

The schematic top view and design parameters of the single-sided, double-ring UMRR unit cell (called UMRR-III) are shown in Figure 1. The corresponding broadside-coupled topology is called BC UMRR-III which has the same conducting strip pattern printed on both faces of the dielectric substrate in the anti-parallel fashion (see Figure 2.a). Two more unit cell topologies (named as UMRR-I and UMRR-II) as well as their broadside-coupled versions (called BC UMRR-I and BC UMRR-II, respectively) are also shown in Figure 2.a. The unit cell UMRR-I

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

has a single U-ring which is the same as the outer (larger) ring of the unit cell UMRR-III. Similarly, the only U-ring of the unit cell UMRR-II is the same as the inner (smaller) ring of UMRR-III. In other words, the double-band structure UMRR-III is the combination of the single-band structures UMRR-I and UMRR-II. The proposed UMRR unit cells are designed on a planar dielectric substrate with relative permittivity $\varepsilon_r = 3$ and loss tangent $\tan\delta_c = 0.002$. Metallic inclusions are made of copper with the thickness $t_{metal} = 0.035$ mm and conductivity $\sigma_{cu} = 5.8 \times 10^7$ S/m. Dimensions of the substrate in the x, y and z directions are 2 mm, 10 mm and 10 mm respectively. The gap distance (g) and strip width (w) are both 0.6 mm.

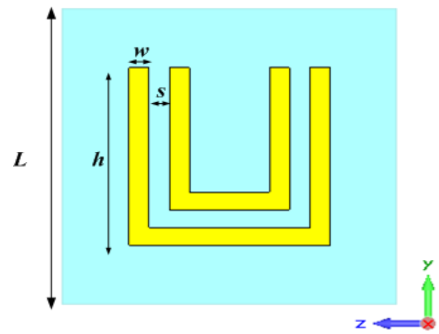
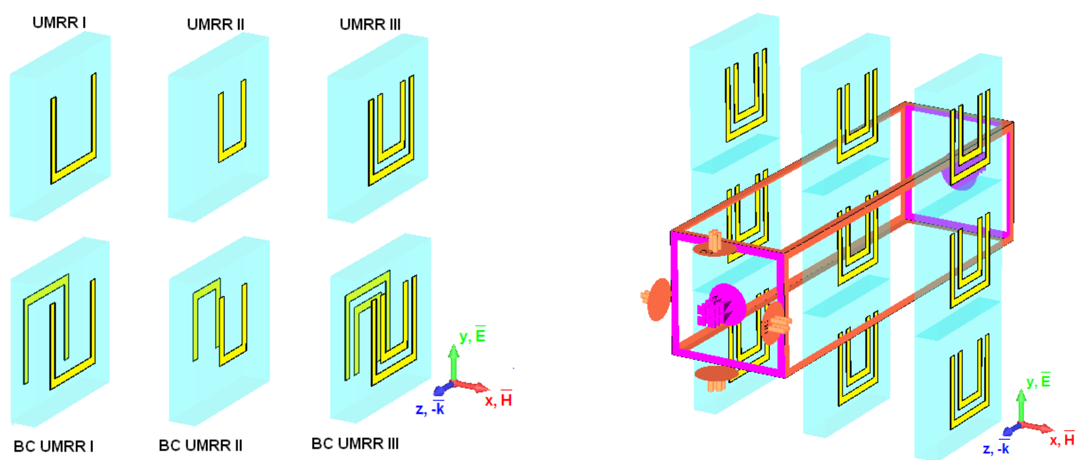


Figure 1. Schematic top view and design parameters of the single-sided double ring UMRR (called UMRR-III)

Simulations of these six different magnetically excited structures are performed by using the CST Microwave Studio (MWS) with frequency domain solver. Field excitation directions are shown in Figure 2. Unit cell boundary conditions are applied along the x and y directions. Open boundary condition is applied along the z direction. Each simulated array is modeled as having infinitely many unit cells with periodicity of 10 mm along the x and y directions as shown in Figure 2.b for the UMRR-III structure, as an example.



a. b.

Figure 2. a. Unit cell topologies of simulated UMRRs. b. Simulated array and field excitations in CST MWS.

3. Results

Transmission spectra for the UMRR-I (blue curve) and BC UMRR-I (red curve) topologies are shown in Figure 3 having single magnetic resonance dips at 7.42 GHz and 5.29 GHz, respectively. The electrical size (u) of a resonator structure is found by the expression $u = D / \lambda_0$ where D is the maximum linear dimension of the unit cell structure (i.e. $D = \sqrt{2}\ L$ for our square shaped unit cells with side length L) and λ_0 is the free space wavelength at resonance frequency. Therefore, the electrical sizes of the UMRR-I and BC UMRR-I are calculated to be 0.350 and 0.249. In other words, the double-sided BC UMRR-I structure is electrically smaller than the single-sided UMRR-I structure by 28.86 percent.

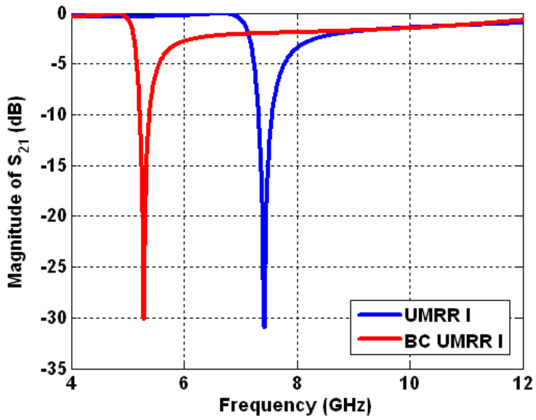


Figure 3. Magnitude spectra for the UMRR-I and BC UMRR-I arrays.

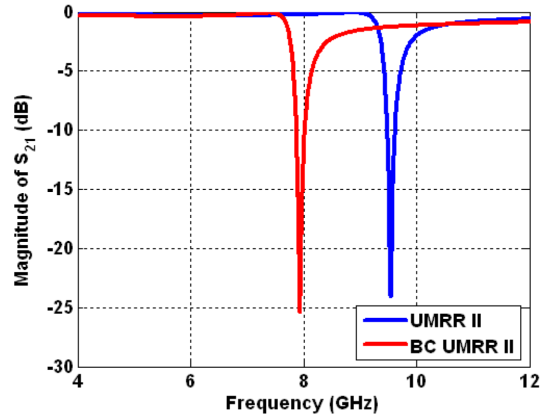


Figure 4. Magnitude spectra for the UMRR-II and BC UMRR-II arrays.

Similarly, the transmission spectra of the UMRR-II (blue curve) and BC UMRR-II (red curve) structures are shown in Figure 4 with single magnetic resonance dips at 9.54 GHz and 7.94 GHz, respectively. Accordingly, the electrical sizes of the single-sided and double-sided topologies are calculated to be 0.450 and 0.374 which means that the broadside-coupled structure is electrically smaller as compared to the UMRR-II structure by 16.89 percent.

Finally, transmission spectra of the double-ring topologies UMRR-III (blue curve) and BC UMRR-III (red curve) are shown in Figure 5. As expected, each of these structures has two magnetic resonances. First resonance dips of UMRR-III and BC UMRR-III are observed at 7.06 GHz and 5.36 GHz, respectively, with the corresponding electrical sizes of 0.333 and 0.253. In other words, at the first resonance, the BC UMRR-III is electrically smaller than the UMRR-III structure by 24.02 percent. Second resonance dips of UMRR-III and BC UMRR-III are observed at 9.54 GHz and 8.51 GHz, respectively. Therefore, the electrical sizes of the UMRR-III and BC UMRR-III at their second resonances are calculated to be 0.450 and 0.401. The broadside-coupled structure is again found electrically smaller by 10.88 percent as compared to the single-sided UMRR-III structure concerning the second resonances. Computed values of resonance frequencies and the corresponding electrical sizes of all structures under investigation are summarized in Table 1.

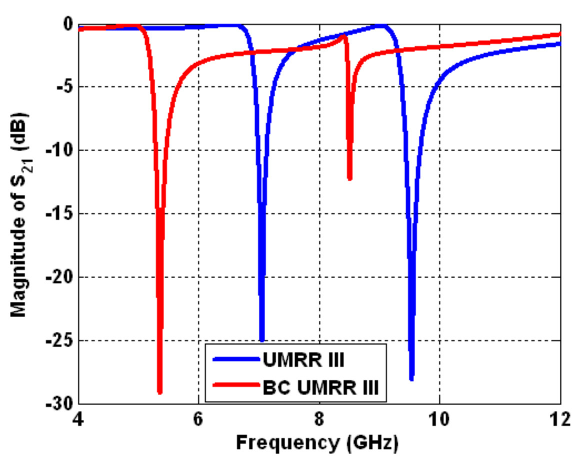


Figure 5. Magnitude spectra for the UMRR-III and BC UMRR-III arrays.

Table 1. Resonance frequencies and electrical sizes for the simulated UMRR topologies.

Structure	Resonance 1		Resonance 2	
	Resonance Freq. (GHz)	Electrical Size - *u*	Resonance Freq. (GHz)	Electrical Size - *u*
UMRR-I	7.42	0.350	N/A	N/A
BC UMRR-I	5.29	0.249	N/A	N/A
UMRR-II	9.54	0.450	N/A	N/A
BC UMRR-II	7.94	0.374	N/A	N/A
UMRR-III	7.06	0.333	9.54	0.450
BC UMRR-III	5.36	0.253	8.51	0.401

4. Conclusion

It is demonstrated in this study that broadside coupling provided by double-sided topology may lead to significant amounts of reduction in the electrical size of U-shaped multiple ring resonator structures. The percentage reductions in the single-band (single-ring) and double-band (double-ring) U-shaped resonators are found to range from 11 percent to 29 percent, approximately. Larger miniaturization effects are observed at smaller resonance frequencies due to broadside coupling. As miniaturization is an important issue for metamaterial design, introduction of the broadside-coupled multiple ring U-Shaped magnetic resonator topology is considered to be a useful contribution to multi-band metamaterial research.

5. References

1. V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Sov. Phys.-Usp.*, **10**, 1968, pp. 509–514.
2. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low-frequency plasmons in thin wire structures," *J. Phys., Condens. Matter*, **10**, 1998, pp. 4785–4809.
3. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microw. Theory Tech.*, **47**(11), 1999, pp. 2075–2084.
4. D. R Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.,* **84**(18), 2000, pp. 4184-4187.
5. E. Ekmekci, G. Turhan-Sayan, "Comparative investigation of resonance characteristics and electrical size of the double-sided SRR, BC-SRR and conventional SRR type metamaterials for varying substrate parameters," *Progress In Electromagnetics Research B,* **12**, 2009, pp.35-62.
6. E. Ekmekci, K. Topalli, T. Akin and G. Turhan-Sayan, "A tunable multi-band metamaterial design using micro-split SRR structures," *Opt. Express,* **17**(18), 2009, pp.16046-16058.
7. E. Ekmekci, and G. Turhan-Sayan, "Single loop resonator: dual-band magnetic metamaterial structure," *Electron. Lett.,* **46**(5), 2010, pp.324-325.
8. K. B. Alici, F. Bilotti, L. Vegni, and E. Ozbay, "Miniaturized negative permeability materials," *Appl. Phys. Lett.*, **91**, 2007, p. 071121.
9. O. Turkmen, E. Ekmekci, G. Turhan-Sayan, "A new multi-ring SRR type metamaterial design with multiple magnetic resonances,'' *Progress in Electromagnetic Research Symposium*, Marrakesh, Morocco, March 2011, in press.
10. O. Turkmen, E. Ekmekci, G. Turhan-Sayan, "Parametric investigation of a new multi-band metamaterial design: U-shaped multiple ring magnetic resonators,'' *IEEE International Symposium on Antennas and Propagation*, Washington, USA, July 2011, submitted.
11. C. Zhu, J. J. Ma, L. Li, C. H. Liang "Multiresonant metamaterial based on asymmetric triangular electromagnetic resonators,'' *IEEE, Antennas and Wirel. Propag. Lett*., **9**, 2010, pp. 99-102,
12. Y. Yuan, C. Bingham, T. Tyler, S. Palit, T. H. Hand, W. J. Padilla, D. R. Smith, N. M. Jokerst, and S. A. Cummer "Dual-band planar electric metamaterial in the terahertz regime ,'' *Opt. Express,* **16**(13), 2008, pp. 9746-9752.