

Compact Triple Band Metamaterial Antenna Based on Modified Electric-field Coupled-LC Resonator

B. D. Bala, M. K. A. Rahim*, N. A. Murad, M. H. Mokhtar

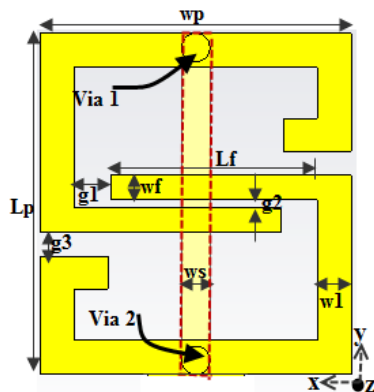
Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: mkamal@fke.utm.my

Article history

Received :30 April 2014
Received in revised form :
25 June 2014
Accepted :15 August 2014

Graphical abstract



Abstract

In this paper, a compact triple band metamaterial antenna based on modified electric-field coupled (ELC) resonator is presented. The modification to the conventional ELC is achieved by the use of strip lines to enhance the capacitive coupling of the capacitive gaps and a stub printed at the back of the resonator. The unit cell's macroscopic parameters were not affected by the structural modifications as the electric moment dominates the magnetic moments in the ELC response. By employing this structure, three resonance frequencies at 1.65 GHz, 3.5 GHz and 5.8 GHz are obtained. The overall size of the antenna is 40 mm × 45 mm ($0.22\lambda_0 \times 0.24\lambda_0$) with the unit cell size of 12 mm × 11 mm ($0.066\lambda_0 \times 0.060\lambda_0$) at 1.65 GHz. The peak gain of 2.10 dBi and radiation efficiency of 97% is obtained at 5.8 GHz. The proposed antenna has advantages of being compact, small and suitable for WiMAX (3.5 GHz) and WLAN (5.8 GHz) applications. The simulated and measured return losses and the radiation patterns are presented and compared.

Keywords: ELC resonator; metamaterial; triple band

Abstrak

Di dalam makalah ini, antenna kompak metabahan tiga jalur berasaskan pengubahsuaian gandingan bidang elektrik penyalun (ELC) dikemukakan. Pengubahsuaian kepada ELC konvensional terhasil dengan menggunakan garis jalur untuk meningkatkan gandingan kapasitif terhadap ruang kapasitif dan stub yang dicetak di belakang penyalun. Parameter berkaitan sel unit mikroskopik tidak terjejas oleh pengubahsuaian struktur kerana momen elektrik menguasai momen magnetik dalam satu tindakbalas ELC. Dengan menggunakan struktur ini, tiga frekuensi resonan pada 1.65 GHz, 3.5 GHz dan 5.8 GHz diperolehi. Saiz keseluruhan antenna adalah 40 mm × 45 mm ($0.22\lambda_0 \times 0.24\lambda_0$) dengan saiz unit sel 12 mm × 11 mm ($0.066\lambda_0 \times 0.060\lambda_0$) pada 1.65 GHz. Gandaan puncak 2.10 dBi dan kecekapan radiasi sebanyak 97% diperolehi pada frekuensi 5.8 GHz. Antena yang dicadangkan mempunyai kelebihan menjadi kompak, kecil dan sesuai untuk kegunaan aplikasi WiMAX (3.5 GHz) dan WLAN (5.8 GHz). Simulasi dan pengukuran untuk kehilangan kembali dan corak radiasi dikemukakan dan dibandingkan.

Kata kunci: Penyalun ELC; metabahan, tiga jalur

© 2014 Penerbit UTM Press. All rights reserved.

1.0 INTRODUCTION

Recently, the idea of complex materials whose electromagnetic responses are simultaneously negative at a specified frequency range has received considerable attention [1]. Metamaterials (MTM) are artificially fabricated inclusions on a specified host medium whose electromagnetic interactions, (electric and magnetic moments) affects the macroscopic effective permittivity and permeability of the bulk composite medium [2]. Typically, a single metallic MTM inclusion can be considered as a resonant LC tank. The geometry and size of the inclusion are greatly influenced by the inductance and capacitance value of the resonant LC tank [2]. Several resonant MTM structures have been reported; some are greatly influence by their magnetic moments

such as split ring resonator (SRR), complementary electric coupled field resonator (CELC) [3], [4] while others by their electric moments such as complementary split ring resonator (CSRR) and electric coupled field resonator (ELC) [5], [6]. MTM has gain an unprecedented recognition in the area of microwave and millimeter wave due to their anomalous behavior near the resonance frequency. For effective electromagnetic radiations, the unit cell size or lattice constant should be much smaller than quarter free space wavelength. Internal diffractions of the structure occur for a unit cell size greater than the free space wavelength [7]. Hence much smaller unit cell size derails its performance if the inductance and capacitance value of the resonance tank are kept too low. ELC resonator can be printed on one sided substrate with shared center stub (inductive) or slot

(capacitive). The formal is inherently dual band due to its structural configurations [8]. However, narrow bandwidth is the major challenges of resonant based MTM antennas.

MTM antennas based on resonant ELC inclusions have been presented in [9]–[12]. In [9], an electrically small MTM antenna based on modified electric field coupled resonator was designed for wide band applications. The capacitive coupling of the ELC was enhanced to obtain wideband characteristics. In [10], a monopole antenna loaded with ELC resonator at the back was designed. The coupling of the ELC with the monopole excites another resonance frequency to obtain a dual band antenna. Monopole antennas were designed using ELC and its complementary counterpart CELC as parasitic meta-resonator to obtain low profile antennas in [11]. A monopole antenna with couple ELC at the back was presented in [12] to obtain a dual band characteristics. It is worth noting that in all configurations, wide or dual band characteristics were obtained when ELC resonator was used as antennas main radiating element or as parasitic elements.

In this paper, a compact triple band MTM antenna based on modified ELC resonator is presented. The proposed antenna employs ELC resonator as the main radiating element. The adjacent capacitive slots are coupled through a strip lines and the inductive stub is printed at the back of the resonator. The modification is to prevent the overlapping of the stub with the strip lines and to enhance the LC coupling without affecting the unit cell’s macroscopic effective parameters. The constitutive effective parameters of the modify ELC is retrieved. The simulated and measured results of the antenna are presented and compare.

2.0 UNIT CELL ANALYSIS AND ANTENNA DESIGN

The proposed modified ELC resonator is shown in Figure 1. The resonator has shared centre stub (inductive) printed at the back connected through inductive vias. The adjacent gaps (capacitive) were coupled through strip lines forming a two finger inter-digital capacitors. The resonator can be approximated as having a resonant LC tank. The modification of the conventional ELC structure is to enhance the LC coupling and maintained its characteristics. The ELC is fabricated on Taconic dielectric substrate of permittivity 3.5, tangential loss of 0.0018 and thickness of 1.52 mm. Table 1 provides the geometrical dimensions of the resonator and the antenna configurations. To provide further insight, the effective constitutive parameters of the modified ELC are retrieved from the complex S-parameters (S₁₁ and S₂₁) using the methods in [13], [14] as shown in Equation (1)-Equation (3):

$$\epsilon_r = \frac{2}{jk_0 d} \frac{1 - S_{21} - S_{11}}{1 + S_{21} - S_{11}} \tag{1}$$

$$\mu_r = \frac{2}{jk_0 d} \frac{1 - S_{21} + S_{11}}{1 + S_{21} - S_{11}} \tag{2}$$

Where, $k_0 = w/c$, d , w and c are the wave number, slab thickness, radian frequency and speed of light respectively. The normalized impedance (Z) is given by the relation [15]:

$$Z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \tag{3}$$

The simulated retrieved parameter of the resonator is shown in Figure 2. Despite the structural modifications the electric moment is dominant over the magnetic moment at lower frequency 1.0

GHz- 3.0 GHz. The effective permittivity is negative at 1.3 GHz – 1.6 GHz, 2.14 GHz-4.07 GHz and 5.4 GHz- 6.3 GHz. This shows that except at resonance frequency, the ELC behaves like a homogeneous material [15].

The geometry of the proposed triple band antenna is shown in Figure 3. The antenna is fabricated on same Taconic substrate as the ELC resonator. A 50Ω transmission line of length 23 mm and width 3.4 mm is used to feed the antenna. The modified ELC resonator is used as the antennas main radiating element. The overall dimensions of the antenna is 40 mm × 45 mm (0.22λ₀ × 0.24λ₀) at 1.65 GHz. The overall size of the ground plane is 21 mm × 45 mm. The length of the microstrip fed line increases the overall size of the antenna and this is to obtain a better impedance matching. For an electrically small antenna, the value of the lowest order spherical mode is given by Chu’s limit [16];

$$Q_{min} = \frac{1}{ka} + \frac{1}{(ka)^3} \tag{4}$$

Where k is the free space wave number and a is the radius of the sphere enclosing the maximum dimension of the antenna with its image if the antenna has a ground plane. The antenna is said to be electrically small if $ka < 1$. For the proposed antenna, the free space wave number (k) at 1.65 GHz and radius of the sphere (a) are found to be 34.55 rad/m and 8.139 mm respectively. Hence $ka = 0.281 < 1$. Computer simulation technology (CST) microwave studio is used to simulate the antenna.

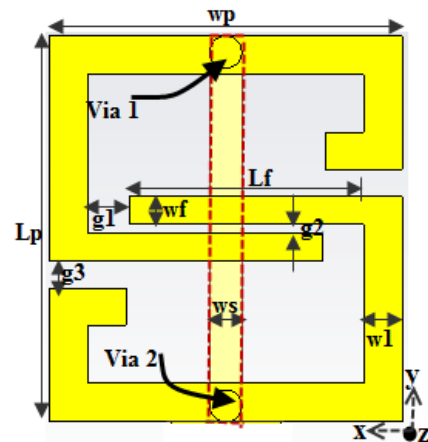


Figure 1 Geometry of the modified ELC resonator

Table 1 Dimensions (mm) of the proposed antenna and the ELC

L	W	Lg	Wt	Lp	Wp	ws
40	45	21	3.4	12	11	1.0
g1	g2	g3	w1	Lf	wf	h
0.8	0.3	0.85	1.2	7.8	1.0	2

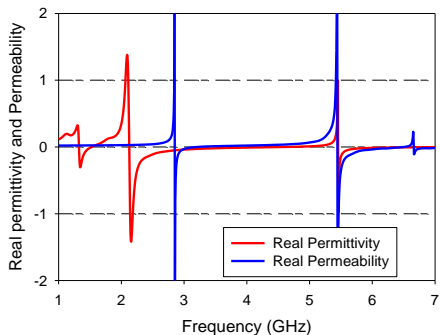


Figure 2 Retrieved effective permittivity and permeability

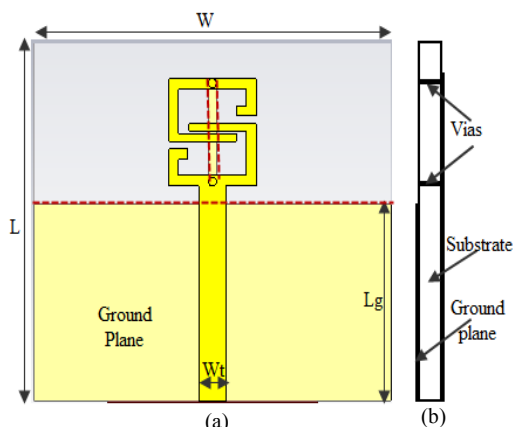


Figure 3 Geometry of the proposed antenna (a) Front View (b) Side view

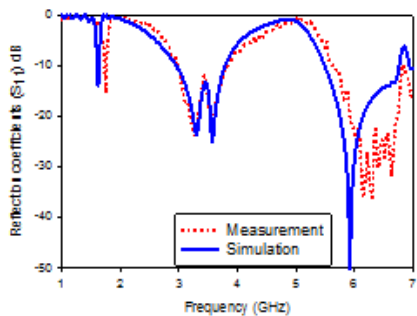


Figure 4 Simulated and measured reflection coefficients (S_{11})

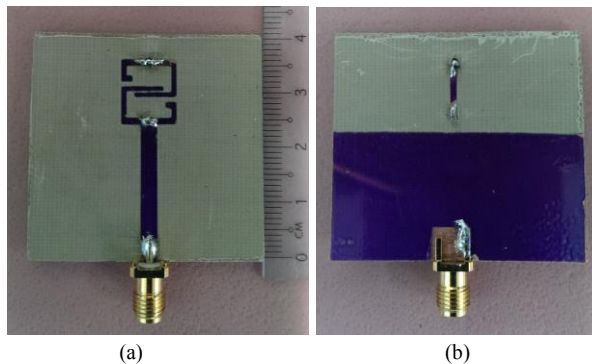


Figure 5 Fabricated prototype (a) Front View (b) Back view

3.0 RESULTS AND DISCUSSION

The measured and simulated reflection coefficients are shown in Figure 4. There is good agreement between the simulated and measured results. Simulated result shows that the proposed antenna resonates at 1.65 GHz, 3.5 GHz and 5.8 GHz. Figure 5 shows the fabricated prototype. Figure 6 shows the surface current distributions at 1.65 GHz, 3.5 GHz and 5.8 GHz. The resonance frequency at 1.65 GHz is dependent on the LC loop formed between the shunted inductive stub and the coupled capacitance between the strip lines. This is evident from the surface current concentrations along the LC loop. The resonance frequencies at 3.5 GHz is as a result of coupling between lower and upper arm of the resonator through the capacitive gap g_2 . Meanwhile, the resonance at 5.8 GHz is attributed to the strong surface current distributions on the shorter arms of both upper and lower part of the resonator. The frequency excitations along on the resonator are as results of different path for loop currents. The measured and simulated radiation patterns for both E- and H-planes are shown from Figure 7 to Figure 9. Good correlation between the measured and simulated radiation pattern is achieved. A monopole-like or directional patterns is obtain for E-plane and omnidirectional for H-plane. The simulated radiation efficiency and measured gains are presented in Figure 10. The gains of 0.22 dBi, 1.56 dBi and 2.10 dBi are obtained at 1.65 GHz, 3.5 GHz and 5.8 GHz respectively. And simulated radiation efficiencies of 31%, 81% and 97% are obtained at 1.65 GHz, 3.5 GHz and 5.8 GHz respectively. The low gain and radiation efficiency at 1.65 GHz is due to loss in the dielectric material as the loop current takes the longer path.

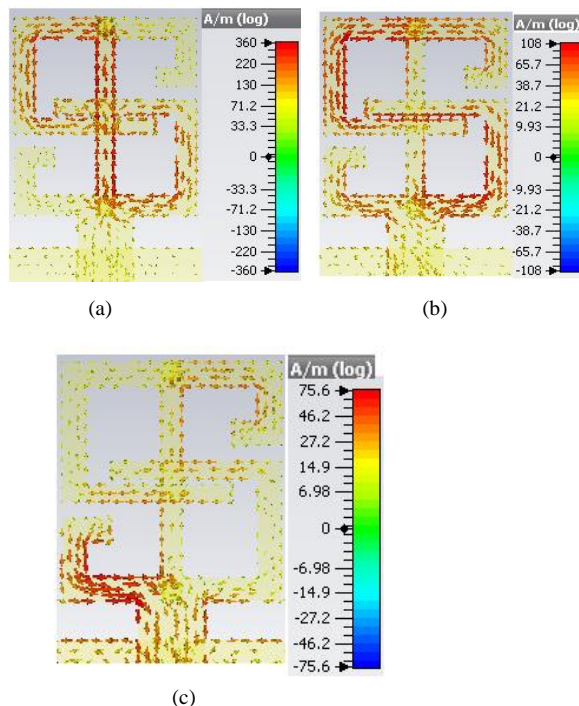


Figure 6 Surface current distributions on the resonator at (a) 1.65 GHz (b) 3.5 GHz and (c) 5.8 GHz

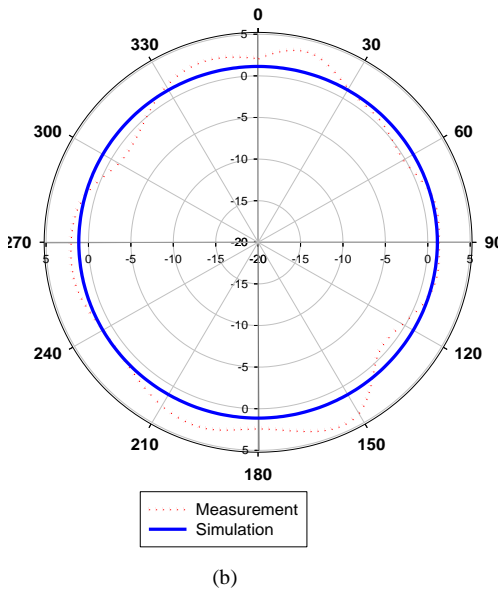
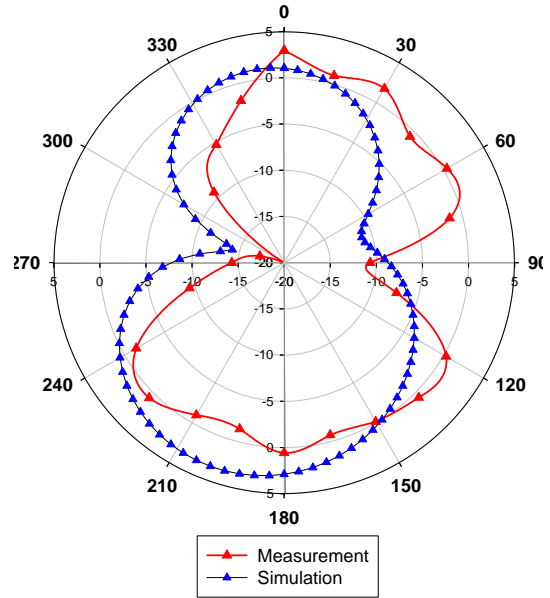
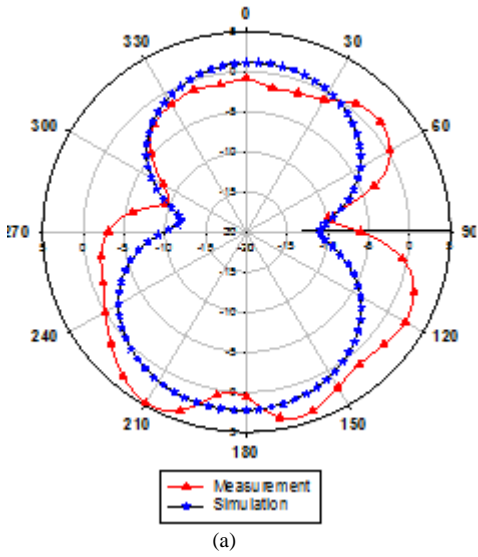


Figure 7 Simulated and measured surface current distributions on the resonator at 1.65 GHz (a) E-plane (b) H-plane

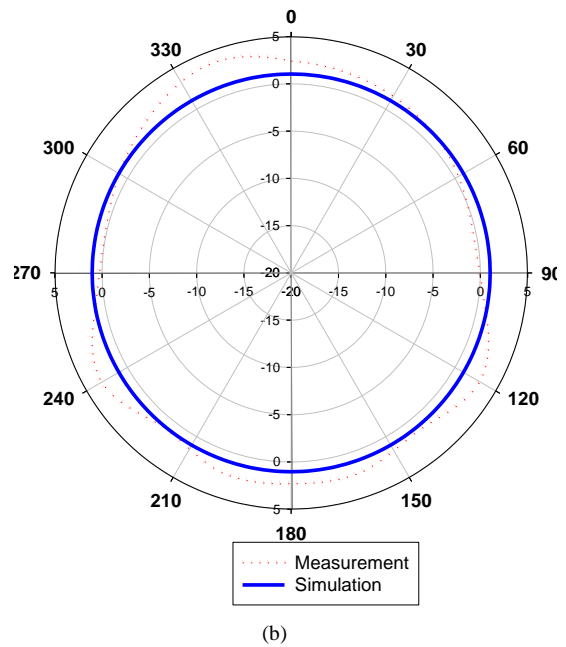


Figure 8 Simulated and measured surface current distributions on the resonator at 3.5 GHz (a) E-plane (b) H-plane

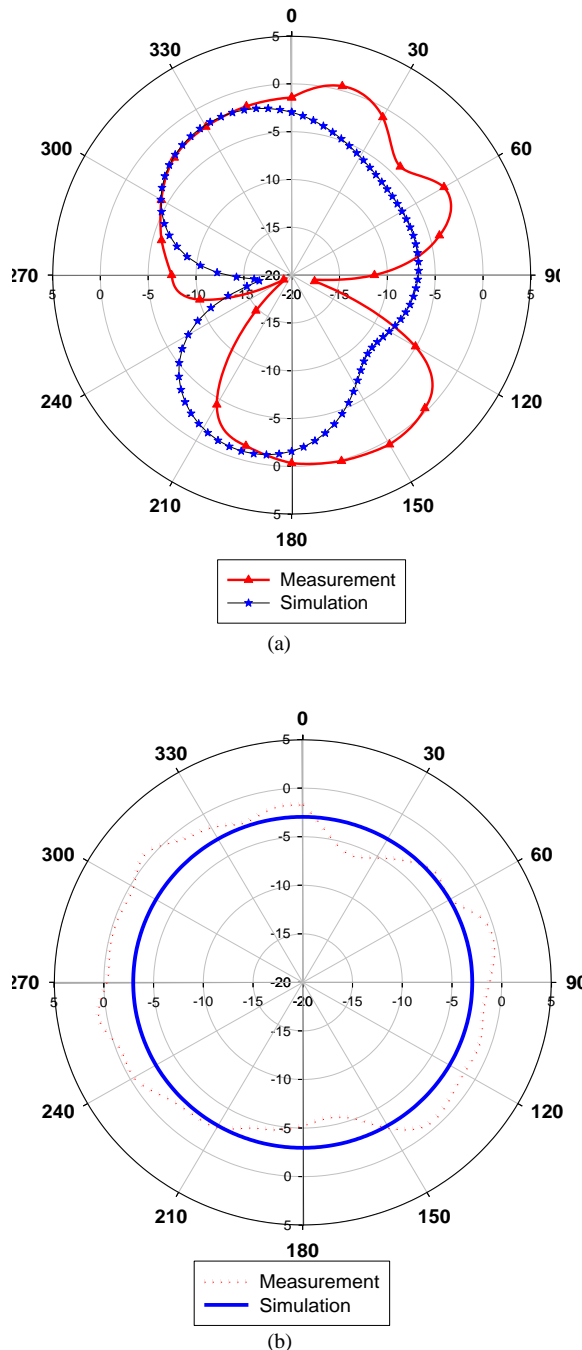


Figure 9 Simulated and measured surface current distributions on the resonator at 5.8 GHz (a) E-plane (b) H-plane

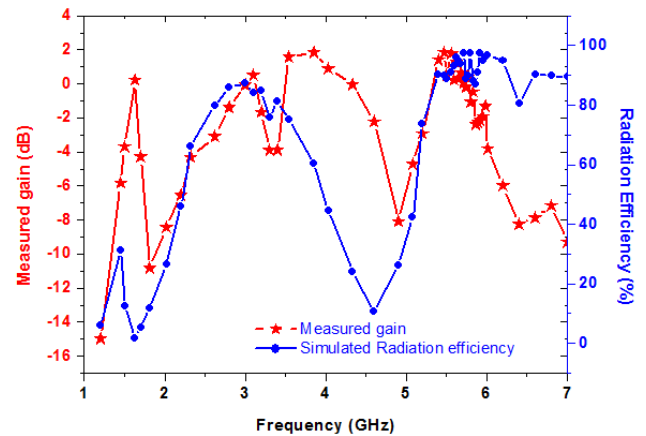


Figure 10 Measured gains and radiation efficiency of the proposed antenna

4.0 CONCLUSION

A compact triple band MTM antenna based on modify electric-field coupled- LC resonator has been designed and presented. The LC coupling of the conventional ELC is enhanced with the modify structure hence the macroscopic constitutive parameters of the conventional ELC were maintained. The antenna was operated at 1.65 GHz, 3.5 GHz and 5.80 GHz. The antenna is compact, miniaturized and suitable for WiMAX (3.5 GHz) and WLAN applications (5.725 GHz-5.825 GHz).

Acknowledgement

The authors thank the Ministry of Higher Education (MOHE) for supporting the research work; Research Management Centre (RMC), School of Postgraduate (SPS), Communication Engineering Department and Universiti Teknologi Malaysia (UTMJB) Johor Bahru for the support of the research under grant no R.J130000.7923, 04H38 and 4L811.

References

- [1] V. G. Veselago. 1968. The Electrodynamics of Substances with Simultaneously Negative Values of ϵ and μ . *Soviet Physics Uspekhi*. 10(4): 509–514.
- [2] W. Withayachumnankul, C. Fumeaux, and D. Abbott. 2010. Compact Electric-LC Resonators for Metamaterials. *Optics Express*. 25(September): 1–5.
- [3] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart. 1999. Magnetism from Conductors and Enhanced Nonlinear Phenomena. *IEEE Transactions on Microwave Theory and Techniques*. 47(11): 2075–2084.
- [4] H.-T. Chen, J. F. O'Hara, A. J. Taylor, R. D. Averitt, C. Highstrete, M. Lee, and W. J. Padilla. 2007. Complementary Planar Terahertz Metamaterials. *Optics Express*. 15(3): 1084–95.
- [5] V. M. Shalaev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and A. V. Kildishev. 2005. Negative Index of Refraction in Optical Metamaterials. *Optics Letters*. 30(24): 3356–8.
- [6] S. Hand, T. H. Gollub, Jonah, Sajuyigbe, S. Smith, D. R. Cummer. 2008. Characterization of Complementary Electric Field Coupled Resonant Surfaces. *Applied Physics Letters*. 93(21): 212504–3.
- [7] C. Caloz, A. Lai, and T. Itoh. 2005. The Challenge of Homogenization in Metamaterials. *New Journal of Physics*. 7: 167–167.
- [8] D. Schurig, J. J. Mock, and D. R. Smith. 2006. Electric-field-coupled Resonators for Negative Permittivity Metamaterials. *Applied Physics Letters*. 88(4): 041109.
- [9] B. D. Bala, N. A. Murad, and M. K. A. Rahim. 2014. Small Electrical Metamaterial Antenna Based on Coupled Electric Field Resonator with Enhanced Bandwidth. *Electronics Letters*. 50(3): 138–139.

- [10] K. Li, C. Zhu, L. Li, and Y. Cai. 2013. Design of Electrically Small Metamaterial Antenna with ELC and EBG Loading. *IEEE Antennas and Wireless Propagation Letters*. 12: 678–681.
- [11] H. Odabasi, F. L. Teixeira, and D. O. Guneş. 2013. Electrically Small, Complementary Electric-field-coupled Resonator Antennas. *Journal of Applied Physics*. 113(8): 084903.
- [12] M. Selvanayagam and G. V. Eleftheriades. 2009. Metamaterial based Wi-Fi Antenna using Electric Field Coupled Resonators. In *2009 IEEE Antennas and Propagation Society International Symposium*. 1–4.
- [13] R. W. Ziolkowski. 2003. Design, Fabrication, and Testing of Double Negative Metamaterials. *IEEE Transactions on Antennas and Propagation*. 51(7): 1516–1529.
- [14] G. Du, X. Tang, and F. Xiao. 2011. Tri-band Metamaterial-Inspired Monopole Antenna with Modified S-Shaped Resonator. *Progress In Electromagnetics Research*. 23(March): 39–48.
- [15] U. C. Hasar. 2011. Retrieval Approach for Determination of Forward and Backward Wave Impedances of Bianisotropic Metamaterial. *Progress In Electromagnetics Research*. 112(January): 109–124.
- [16] D. F. Sievenpiper, D. C. Dawson, M. M. Jacob, T. Kanar, S. Kim, J. Long, and R. G. Quarfoth. 2012. Experimental Validation of Performance Limits and Design Guidelines for Small Antennas. *IEEE Transactions on Antennas and Propagation*. 60(1): 8–19.

