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Design of Compact Bend Triangular Resonator for Wide Band Application

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Abstract—The current wireless technology demands wide frequency operation, like WLAN 5 GHz band, which requires 12.75% frequency bandwidth. In this paper, a unit cell metamaterial structure is proposed, which consists of 4 compact bend triangular resonators (CBTRs) that offer wideband frequency rejection. The single negative metamaterial based resonators give band rejection response, but it is generally bandwidth limited. With the proposed unit cell, rejection bandwidth of 16.78% for rejection level of −12 dB is achieved. It can be further increased by increasing the order of unit cells. The proposed unit cell structure is analyzed for the resonant frequency of 5.5 GHz, and the design is suitable for the application where 15% or more rejection band is required.

1. INTRODUCTION

Metamaterials structures are artificially engineered structures, which show different electromagnetic properties not found in the nature. The electromagnetic properties, such as effective electrical permittivity (ε_r), magnetic permeability (μ_r), and refractive index (η), are negative over specific range of frequencies, then the structure is known as a left-handed metamaterial or double negative metamaterial [1–3]. Double negative metamaterial structures give passband response, whereas single negative one gives stopband response. A refractive index with negative values is also possible, and it is not against the laws of physics and is presented in the theoretical analysis on metamaterial in 1967 by Soviet physicist Veselago [4]. According to the history of metamaterial, these structures act as resonators and give narrow band response, with nearly 3% of bandwidth. To achieve wider bandwidth, multiple resonators are used at adjacent frequencies; otherwise, the number of resonators is increased, but doing so leads to increase in the overall dimensions of metamaterial structures.

The unit cells contain two broken ring shaped metallic structures, known as Split Ring Resonator (SRR). This SRR is exposed to electromagnetic waves and shows a resonant response [5]. The exposed magnetic field induces the current into the rings of SRR, and gap between the rings does not allow the current to flow around the ring and creates coupling capacitance in the structure. Due to additional capacitance, the resonance frequency of the structure shifts to lower frequency. In 2004, Falcon et al. proposed a concept of complementary SRR, in which SRR structure is etched out from the ground plane of microstrip transmission line [6]. In [7], a complementary SRR loaded microstrip transmission line is presented to design ultra-wideband filters with passband and stopband characteristics. The microstrip transmission line is a right handed structure, and if transmission line gets connected with short circuited stub, then the structure is called as composite right/left handed (CRLH) metamaterial. CRLH metamaterial structure resonates at two different frequencies.

Single negative metamaterials structures are used for the reduction of mutual coupling between closely spaced patch antennas. In [8], the authors proposed a complementary folded SRR to improve isolation between probe feed patch antennas. In [9], the electromagnetic behavior of the SRR and

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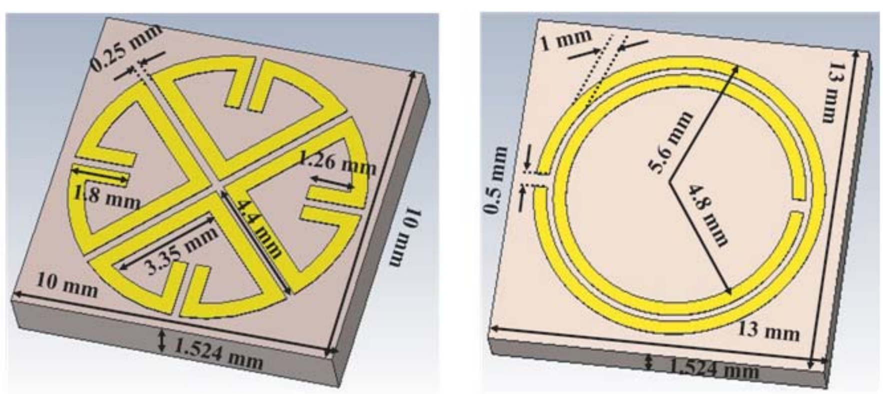
complementary SRR are presented and analyzed using equivalent circuit model. Metamaterial structures are widely studied for multiple applications, and it is observed that metamaterial structure response is bandwidth limited, so an approach is attempted to design wideband and high rejection resonator [10]. The metamaterial structures are loaded in the transmission line in [13, 14], whereas in [15–17], the complementary unit cells are implemented in ground plane of transmission line to get stopband response. In this paper, the proposed unit cell consists of 4 compact bend triangular resonators (CBTRs). The design is simulated, fabricated, and tested for number of order up to 3. The proposed unit cell structure has stopband response for WLAN 5 GHz band. The resonance frequency bandwidth and rejection level can be controlled by choosing appropriate number of order of the proposed unit cell.

2. DESIGN AND ANALYSIS

2.1. Design of CBTR Metamaterial Structure

The compact bend triangular resonator (CBTR) has a triangular structure with one arm curved and broken. The end points of broken arm are bended inwards, to utilize available space. The modification helps to increase electrical size of resonator, by increasing inductance and coupling capacitance. The proposed unit cell consists of four CBTRs as shown in Fig. 1(a). The structure is simulated in CST microwave studio. In the simulation, Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) are assigned as the boundaries of unit cell, and the two boundaries are orthogonal to each other. The proposed unit cell is compared with traditional SRR, and both structures are designed on an FR-4 substrate of thickness 1.524 mm and $\varepsilon_r = 4.3$ to resonate at 5.5 GHz. The traditional SRR dimension is



(a) (b)

Figure 1. Geometry of (a) proposed unit cell, (b) traditional SRR.

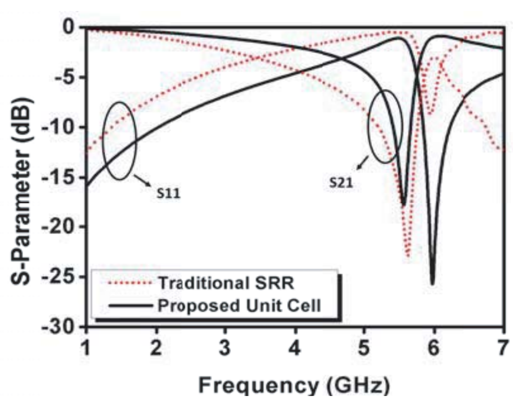


Figure 2. Comparison between traditional SRR and proposed unit cell.

$13 \times 13\,\text{mm}^2$, whereas the proposed unit cell has a dimension of $9 \times 9\,\text{mm}^2$, which shows compactness of the proposed unit cell. The unit cell simulation results of traditional SRR and proposed unit cell are shown in Fig. 2, and it can be seen that the two structures have the same resonance frequency.

2.2. Electromagnetic Properties of Unit cell

Metamaterial structures are engineered structures, having effective medium electromagnetic (EM) properties not common in nature, and these properties are frequency dependent. To extract the medium properties, in the presence of EM fields, PEC and PMC boundary conditions are considered. Signal propagation in the medium depends upon effective electromagnetic properties of medium. The electromagnetic properties of medium are permittivity, permeability, and refractive index. If effective permittivity and permeability of medium have positive values, then medium is called as Right Handed Medium (RHM), and if both parameters have negative values, then it is called as Left Handed Medium (LHM) or metamaterial. If the two parameters have opposite polarity values, then it is called as Single Negative Medium (SNM). RHM and LHM show property to allow signal to pass through. SNM does not allow the signal to pass, but it blocks the signal.

In the unit cell simulation, the incident wave is plane wave with uniform amplitude and phase, and PEC-PMC boundaries define the electric and magnetic field direction (polarization). Under these simulation conditions, the fields cannot penetrate the boundaries, and the field values outside the structure are equal to zero. The primary parameter is S_{21} amplitude and phase in simulation results, so the unit cell and single metamaterial structure simulation are exactly the same.

In the full array or periodic simulation, coupling and decoupling between unit cells is taken into account, and depending on the array factor, the field distribution/radiation varies. For periodic structures like frequency selective surfaces (FSS) and metasurfaces, floquet boundary conditions are generally opted for simulation. Floquet boundary in unit cell allows incident plane waves at arbitrary angles, which is not possible with PEC-PMC boundaries.

Metamaterial properties of unit cell can be calculated using S-parameter. A robust method [11] is opted and implemented in MATLAB tool to calculate effective permittivity and permeability of unit cell. After processing MATLAB code, real values of effective permittivity, permeability, and refractive index are considered for analysis and presented in Fig. 3. It can be observed in Fig. 3 that real value of permeability has positive polarity, but effective permittivity has negative value for frequency range 5.5 GHz to 5.9 GHz with peak value of −22 at 5.7 GHz. Due to negative permittivity signal attenuates for 5.5–5.9 GHz which creates stopband response for design.

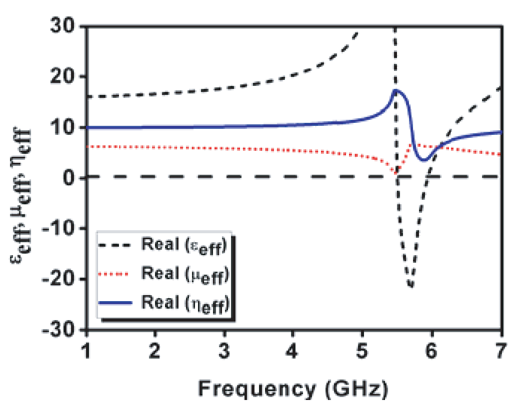
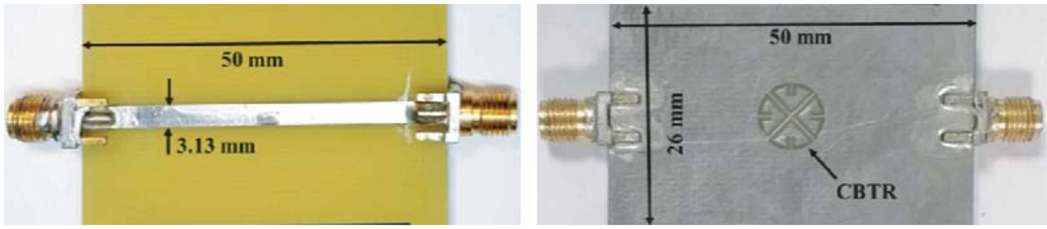


Figure 3. Effective permittivity (ε_{eff}), permeability (μ_{eff}) and refractive index (ε_{eff}) of proposed unit cell.

2.3. CBTRs Loaded Microstrip Line

The $50\,\Omega$ impedance microstrip line is designed on an FR4 substrate ($\varepsilon_r = 4.3$, $h = 1.524\,\text{mm}$) of size $26 \times 50\,\text{mm}$. The microstrip line width is 3.13 mm, and length is 50 mm. The fabricated design



(a) Micro-strip Line (b) Grond Plane

Figure 4. The fabricated proto of CBTR loaded microstrip line.

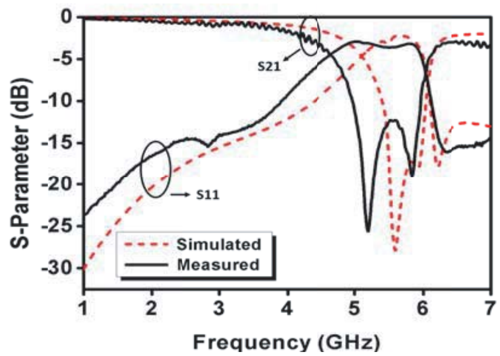


Figure 5. S-parameter result of CBTR loaded microstrip line.

proto image is shown in Fig. 4. The complementary unit cell is aligned with respect to the center of microstrip line. The unit cell gets exposed to the electric and magnetic fields generated from microstrip line. The unit cell shown in Fig. 1(a) and its complementary are approximately dual of each other. The complementary of unit cell response to electric field is approximately the same as the unit cell response of magnetic field [12]. The simulated and measured S-parameter results are shown in Fig. 5. In the measured result, it is observed that the frequency bandwidth is 16.78% for -12 dB rejection (S_{21} dB), and resonance center frequency is 5.5 GHz. The simulated and measured results also show that the design has low pass filter response with -0.5 dB insertion loss and return loss of -15 dB at 2 GHz, and -1.6 dB insertion loss and return loss of -10 dB at 3.9 GHz.

2.4. Equivalent Circuit Model of CBTRs Loaded Microstrip Line

The equivalent circuit model of proposed CBTR loaded microstrip line is presented in Fig. 6. In this circuit, the microstrip line series inductance is presented as $L0$ and coupling capacitance between

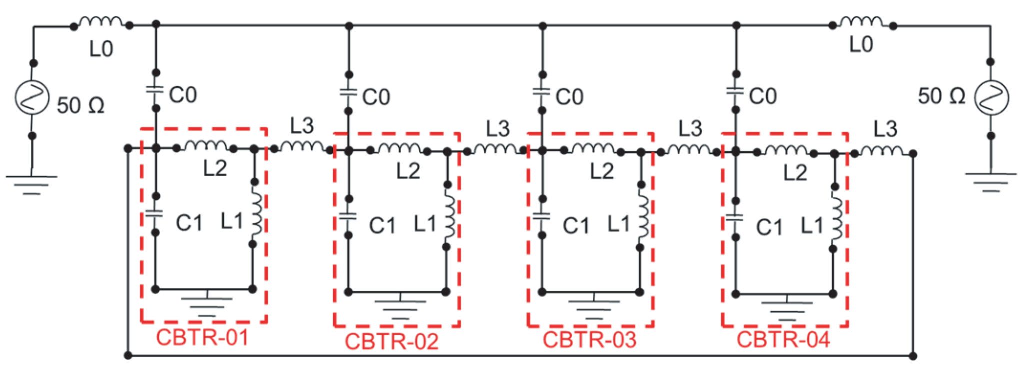


Figure 6. Equivalent circuit model of CBTRs loaded microstrip line.

microstrip line and CBTR as $C0$. The lossless model is considered in equivalent circuit. The unit cell is combination of four CBTRs, and each CBTR is modeled as shunt inductance $L1$, series inductance $L2$, and shunt capacitance $C1$. All four CBTRs are inductively coupled with their neighboring CBTR, presented as $L3$ in Fig. 6. The values of equivalent circuit components are given in Table 1. The circuit is simulated in Keysight ADS Simulator and compared with EM (electromagnetic) simulation result in Fig. 7. The simulation results have close matching and same resonance frequency.

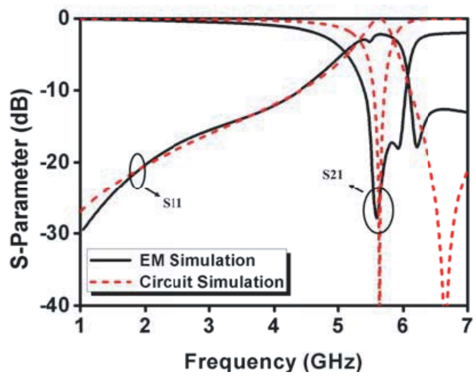


Figure 7. Simulated return loss of CBTR loaded microstrip line.

Table 1. Equivalent circuit parameters and its value.

Parameters	Values	Description
$L0$	0.4 nH	Microstrip line series inductance
$C0$	0.15 pF	Coupling capacitance between microstrip line and CBTR
$L1$	1.0 nH	CBTR Shunt Inductance
$C1$	0.53 pF	CBTR Shunt Capacitance
$L2$	0.5 nH	CBTR Series Inductance
$L3$	0.6 pF	Coupling Inductance between CBTRs

3. ORDER ANALYSIS

The impact of increasing order of unit cell is analyzed in terms of rejection and frequency bandwidth. In this paper, the design with $N = 1$, 2 and 3 is simulated, fabricated, and measured, where unit cells are placed at a distance of 1 mm away from each other. Fabricated prototype and its dimensions are shown in Fig. 8.

The simulated and measured S_{21} (dB) results are presented in Fig. 9 for $N = 1$, 2 and 3, and it can be observed that with increasing number of order (N) of unit cell, the attenuation/rejection (S_{21} (dB)) and frequency bandwidth response also increase. It can be observed that resonance frequency is shifted towards lower frequency by 100 MHz with addition of unit cell. For $N = 3$, the fractional bandwidth of 27.32% is achieved for a measured S_{21} (dB) -20 dB and below, which is sufficient for modern wireless application like WLAN 5 GHz band. The number of order for unit cell can be chosen based on application requirement. The simulated and measured results also show that the design has low pass filter response with -1.6 dB insertion loss and return loss of -10 dB at 3.9 GHz, and it does not change with increasing number of order (N) of unit cell up to $N = 3$.

The summary of the simulated and measured results is tabulated in Table 2. The resonance frequencies are the same for simulated and measured results, but there is difference in fractional bandwidth. This difference may come from different available grades of material in FR4 substrate like TG130, High TG, and FR4-Rogers. The measured result is validated with 2 design protos, and it is the same for both design protos.

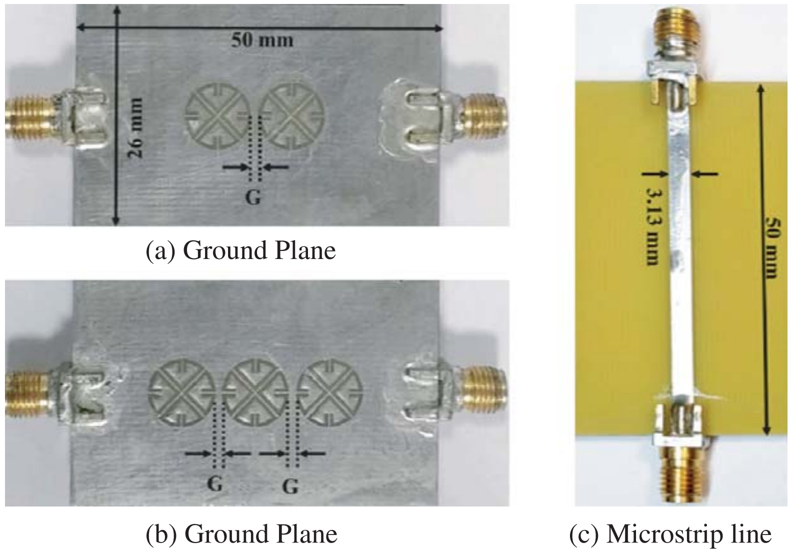


Figure 8. Fabricated prototype for (a) $N = 2$, (b) $N = 3$, (c) microstrip line.

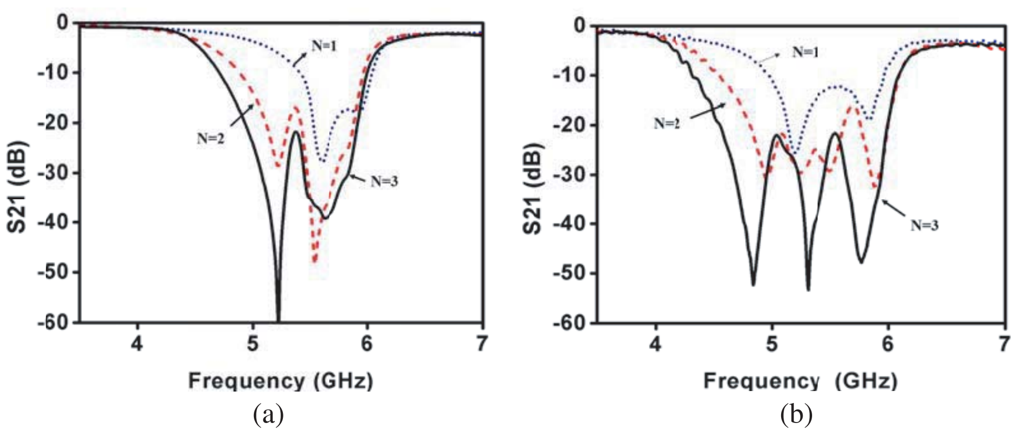


Figure 9. (a) Simulated and (b) measured S_{21} (dB) of CBTRs loaded microstrip line with increasing order.

Table 2. Simulated and measured data summary of order analysis.

Order	S_{21} (dB)	Simulated		Measured	
		Frequency Range	% Bandwidth	Frequency Range	% Bandwidth
$N = 1$	< -12 dB	5.42–6.01 GHz	9.77%	5.02–5.94 GHz	16.78%
$N = 2$	< -16 dB	5.04–5.94 GHz	16.39%	4.73–6.02 GHz	23.96%
$N = 3$	< -20 dB	4.93–5.90 GHz	17.92%	4.55–5.99 GHz	27.32%

Parametric study is carried out to find the impact of separation between unit cell (denoted as G in Fig. 8), and the 3rd order of unit cell ($N = 3$) is considered for it. The response of variation in parameter G is shown in Fig. 10. It can be seen that the rejection, S_{21} (dB), increases with parameter G, but frequency bandwidth response decreases. So it is important to choose value of parameter G such that it meets the requirement of rejection level and rejection bandwidth. In this paper, for the analysis of unit cell, the value of $G = 1$ mm is considered. For $G = 1$ mm, 3rd order unit cell gives frequency response for band 4.55–5.99 GHz for -20 dB of S_{21} (dB).

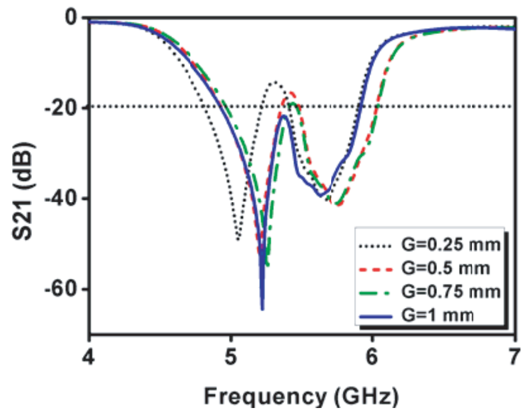


Figure 10. Variation in S_{21} (dB) with the change in gap (G).

A comparison of the proposed unit cell with References [13] to [17] is presented in Table 3 with respect to -10 dB rejection (S_{21}). In [16], fractional bandwidth of 49.22% is reported for 3rd order unit cell, where all unit cells have different dimensions, and with these combinations, it is difficult to achieve -20 dB rejection. It can be seen that the proposed unit cell in this paper has compact size and gives wider fractional bandwidth than reference designs.

Table 3. Filter characteristics — Compared.

Ref. No.	Dimension	Substrate	Order	S_{21} (dB)	Frequency Range	% Bandwidth
[13]	$16 \times 16\,\text{mm}^2$	$\varepsilon_r = 4.4$, $h = 1.6\,\text{mm}$	1	< -10	2–2.34 GHz	15.66%
[14]	$3 \times 21.1\,\text{mm}^2$	$\varepsilon_r = 4.4$, $h = 1.6\,\text{mm}$	1	< -10	3.6–4.46 GHz	21.33%
[15]	$15.4 \times 15.4\,\text{mm}^2$	$\varepsilon_r = 4.4$, $h = 1.5\,\text{mm}$	1	< -10	3.1–3.4 GHz	9.23%
[16]	$18 \times 5.6\,\text{mm}^2$	$\varepsilon_r = 2.33$, $h = 0.508\,\text{mm}$	3	< -9	4.84–8 GHz	49.22%
[17]	$24.9 \times 6\,\text{mm}^2$	$\varepsilon_r = 10.2$, $h = 1.27\,\text{mm}$	4	< -10	2.25–3.11 GHz	32.08%
This Work	$9 \times 9\,\text{mm}^2$	$\varepsilon_r = 4.3$, $h = 1.524\,\text{mm}$	1	< -10	4.97–5.96 GHz	18.11%
	$19 \times 9\,\text{mm}^2$		2	< -10	4.56–6.09 GHz	28.37%
	$29 \times 9\,\text{mm}^2$		3	< -10	4.32–6.09 GHz	34.00%

4. CONCLUSION

In this paper, a unit cell consists of four CBTRs is proposed, for the purpose of improving stopband frequency bandwidth and stopband attenuation, S_{21} (dB). For the resonant frequency of 5.5 GHz, traditional SRR dimension is $13 \times 13\,\text{mm}^2$, while proposed unit cell dimension is $9 \times 9\,\text{mm}^2$, which shows compact nature of the proposed unit cell. The proposed unit cell shows property of single negative metamaterial, which gives fractional bandwidth of 16.78% for -12 dB rejection. The stopband frequency bandwidth and rejection level are further improved by increasing order of unit cell, and 27.32% fractional bandwidth is noted for 3rd order unit cell for -20 dB of rejection. The proposed unit cell can be utilized for wideband rejection application like isolation improvement in MIMO antennas or to design filters.

REFERENCES

1. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, Vol. 292, No. 5514, 77–79, 2001.
2. Smith, D. R. and N. Kroll, "Negative refractive index in left-handed materials," *Phys. Rev. Letter.*, Vol. 85, No. 14, 4184–4187, 2000.
3. Cory, H. and A. Barger, "Surface wave propagation along a metamaterial slab," *Microwave and Optical Technology Letters*, Vol. 38, No. 5, 392–395, Sep. 5, 2003.
4. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, Vol. 10, 4, Jan.–Feb. 1968.
5. Wartak, M. S., K. L. Tsakmakidis, and O. Hess, "Introduction to metamaterials," *Physics in Canada*, Vol. 67, No. 1, Jan.–Mar. 2011.
6. Falcone, F., T. Lopetegi, J. D. Baena, and R. Marques, "Effective negative-ε stopband microstrip lines based on complementary split ring resonator," *IEEE Microwave and Wireless Component Letters*, Vol. 14, No. 6, 280–282, Jun. 2004.
7. Jegadeesan, S., J. Vijayakrishnan, N. Chandrasekar, and S. Gnanasundar, "Design of compact Ultra Wide Bandpass Filter (UWBPF) with metamaterial — Comparison between different CSRRs," *3rd International Conference on Signal Processing, Communication and Networking (ICSCN)*, 1–6, Chennai, 2015.
8. Habashi, A., J. Nourinia, and C. Ghobadi, "Mutual coupling reduction between very closely spaced patch antennas using low-profile Folded Split-Ring Resonators (FSRRs)," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 862–865, 2011.
9. Baena, J. D., et al., "Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 4, 1451–1461, Apr. 2005.
10. Naskar, M. A., M. Tamrakar, and D. Thiripurasundari, "Compact 'V' shaped metamaterial based resonator for wide band rejection," *2017 International Conference on Nextgen Electronic Technologies: Silicon to Software (ICNETS2)*, 88–91, Chennai, 2017.
11. Chen, X., et al., "Robust method to retrieve the constitutive effective parameters of metamaterials," *Physical Review, E, Statistical, Nonlinear, and Soft Matter Physics*, Vol. 70, No. 1, Pt. 2, 016608, 2004.
12. Falcone, F., T. Lopetegi, J. D. Baena, R. Marques, F. Martin, and M. Sorolla, "Effective negative-/spl epsiv/ stopband microstrip lines based on complementary split ring resonators," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No. 6, 280–282, Jun. 2004.
13. George, B., N. S. Bhuvana, and S. K. Menon, "Design of edge coupled open loop metamaterial filters," *2017 Progress In Electromagnetics Research Symposium — Spring (PIERS)*, 2483–2488, St. Petersburg, 2017.
14. Hammad, Y. T., M. A. Abdalla, and A. F. Daw, "A compact band stop filter with sharp stopband response using D-CRLH configuration," *12th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)*, 004–006, 2018.
15. Abessolo, M. A. A., Y. Diallo, A. Jaoujal, A. Moussaoui, and N. Aknin, "Stop-band filter using a new metamaterial Complementary Split Triangle Resonators (CSTRs)," *Applied Computational Electromagnetics Society Journal*, Vol. 28, No. 4, 353–358, 2013.
16. Atallah, H. and E. Hamad, "Compact CSRRs-based metamaterial band stop filter with controlled rejection band," *IEEE — New Paradigms in Electronics and Information Technologies (PEIT011) International Conference*, Alexandria, Egypt, Oct. 2011.
17. Sassi, I., L. Talbi, and K. Hettak, "Compact multi-band filter based on multi-ring complementary split ring resonators," *Progress In Electromagnetics Research C*, Vol. 57, 127–135, 2015.