Miniaturized and enhanced bandwidth Marchand balun using CSRR

Partha Kumar Deb1 | Tamasi Moyra1 | Bidyut Kumar Bhattacharyya2

1Department of Electronics and Communication Engineering, National Institute of Technology Agartala, India
2Georgia Institute of Technology, Department of Nano Technology/PRC, Atlanta, USA

Abstract
A novel and miniaturized Marchand balun is proposed using two quarter-wave edge coupled transmission line and two complementary split-ring resonators (CSRR) unit cell in the ground plane. These coupled lines are joined with the help of an uncoupled microstrip line. The short circuit and open circuit terminations are assigned at the specified ports. Two rectangular shaped CSRR cells improve the circuit performance. A step impedance technique has been applied at the balanced ports to enhance the bandwidth. This proposed design produces a fractional bandwidth of 18.75% at the centre frequency with a maximum magnitude and phase imbalance of 0.56 dB and 0.85°. This design occupies a total circuit area of 0.515 λg (30.72 mm) × 0.279λg (16.63 mm). The circuit has been designed at 2.4 GHz centre frequency using low-cost FR4 substrate material. The simulated and measured results are in acceptable accord in terms of magnitude and phase response.

1 | INTRODUCTION

A balun is a transformer that converts an unbalanced signal to a balanced one and vice-versa [1]. The signal appearing at two balanced ports are of the same amplitudes with 180° phase shift between them. Several balun applications improve noise performance and expand the dynamic range of different microwave circuits such as antenna feeding networks, balanced mixers, push-pull amplifiers and multipliers [2–4]. One of the most popular distributed type passive balunstructures is Marchand balun (MB), which delivers a single-ended signal to a balanced signal, as shown in Figure 1(a). This kind of balun structure comprises two symmetrical quarter-wave coupled line sections with open and short circuit termination at specified ports. These baluns provide enhanced bandwidth (BW) and maintain good phase difference and power distribution [5].

Several research studies have been done by researchers for the miniaturization of MB such as in [6], a balun was proposed with increased isolation between the balanced ports using a power divider and 180° phase shifter, which give wider BW but resulted in increased circuit area. In [7], the authors proposed a balun fabricated using RT Duroid 6006 that gives higher BW but at the cost of larger size and expensive substrate material. A miniaturized dual-band MB was designed in [8] using low temperature cofired ceramic material, which increases the design complexity. In [9], the authors had designed a broadband MB using slot coupled microstrip line in a two-layered dielectric substrate with three metallic layers that increase fabrication complexity and circuit size. In another study [10], a miniaturized single-layer microstrip MB was designed where the author had introduced left-handed transmission lines between two coupled lines, which provide increased coupling among the coupled lines. But this proposed technique still consumes a higher circuit area at the operating frequency and without any BW enhancement.

A simple and compact single layer MB is proposed, which operates in 2.4 GHz frequency. Two rectangular-shaped complementary split-ring resonators (CSRR), which show metamaterial properties, play a vital role in the miniaturization [11–13] of the balun circuit. Among the two-parallel lines of each edge coupled transmission line, one line is directly connected with another one through an uncoupled microstrip line. Two balanced ports are connected in another line, as shown in Figure 1(b), where step impedance arrangement helps achieve enhanced BW.

This study is organizes as follows: Section 1 is about the brief introduction of MB and different researches in this field, Section 2 is about the structural description of MB, in
Section 3, an investigation of conventional and modified CSRR is shown, in Section 4, parameter extraction of CSRR is done along with the justification of metamaterial behaviour. In Section 5, the designing of miniaturized MB is given, the magnitude and phase response of conventional and proposed MB (with and without CSRR) of Figure 1 are also discussed. In Section 6, simulated and measured results of the proposed MB are plotted and a detail discussion about the obtained result is given. A detail performance comparison between the proposed and existing designs is given in Section 7. The study concludes in Section 8.

2 | STRUCTURAL DESCRIPTION OF MARCHAND BALUN

Figure 2 shows the proposed MB. An uncoupled line of length 8.74 mm is introduced to connect the two symmetrical quarter-wave coupled lines. This line is bent and created a ‘U’ like shape to miniaturize the overall circuit area requirement. The unbalanced and balanced port impedances are fixed at 50 Ω for convenience. Two CSRR cells have been introduced in the ground plane, which is placed equidistance from the middle of the circuit, as shown in Figure 2(b). The balanced ports have been connected with two rectangular shaped metallic pads for impedance matching. Short circuit termination has been achieved through vias to ground having 0.3 mm diameter. In practical circuit implementation, via connection with a copper wire of 0.3 mm diameter they are inserted into the hole drilled from signal plane to ground plane and soldered in both the planes with a copper plate of the substrate material.
3 | INVESTIGATION OF THE CONVENTIONAL AND MODIFIED COMPLEMENTARY SPLIT-RING RESONATOR

Split-ring resonator (SRR) is a negative image of SRR and one of the crucial components of the metamaterial. In 2001, the authors in [14] showed that the 2D array of copper wires and SRRs could display the negative index material characteristics at the operating frequency. Pendry et al. disclosed that SRR possesses negative permeability (μ) and copper wires possess negative permittivity (ε) when magnetic (H)-field is functional in the axial direction [15–18].

CSRR unit cells are excited by electric (E)-field applied parallel to the axis. When H-field is applied in a particular direction, the cross-polarization effect permits the CSRR (/SRR) cell to be driven by the H-field (/E-field). This effect rests on the positioning of the CSRR cell. When the ring openings are along the host transmission line, a small quantity of E- and H-field exists, which must be calculated. The conventional unit cell and its lumped circuit equivalent [19] is shown in Figure 3(a) and (b), respectively.

In general, the CSRR is used to produce a stop band in the resonating frequency (f = 1.43 GHz for the unit cell shown in Figure 3(a)), which is shown in Figure 4(a). From Figure 4(a), it can be noticed that the magnitude and phase angle values of S11 and S22 are equal for the CCSRR unit cell. For this case, the ring openings are normal to the host transmission line, i.e. the line is oriented in X-axis, as shown in Figure 3(c) [18]. In the MCSRR cell, ring openings are rotated by 90° that disrupts the orientation of CCSRR as portrayed in Figure 3(c). Consequently, the responses were also modified, resulting in inequality between the magnitude and phase angle values of S11 and S22 as plotted in Figure 4(b). It is explained in [19, 20] that for parameter extraction of CSRR unit cell with ring openings aligned parallel to the host line, it is required to consider the cross-polarization effect and the parameter extraction technique without rotation fails. This cross-polarization effect has been incorporated by considering mutual inductance between the host line and rings (as shown in Figure 3(b)) [19].

L, Cc, Ls,Cs, R and M represent the inductance of the host line, the coupling capacitance between the signal and ground plane, equivalent inductance and capacitance of CSRR cell, lossy resistance and the mutual inductance between the host line CSRR rings as depicted in equivalent circuit (EC) in Figure 3(b) and (d).

4 | PARAMETER EXTRACTION OF CSRR AND ITS JUSTIFICATION AS METAMATERIAL

It is depicted in [15–18] that for parameter extraction of CSRR unit cell following mathematical expression needs to be considered:

\[
\eta = \frac{1}{Kd} \cos^{-1}\left( \frac{1}{2S^{11}} \left(1 - S^{11}e^{jS^{22}}\right) \right) \quad (1)
\]

\[
K = \frac{2\pi f(j)}{C} \quad (2)
\]

**Figure 3** (a) Conventional complementary split-ring resonator (CCSRR) unit cell, (b) its lumped equivalent circuit, (c) modified complementary split-ring resonator (MCSRR) and (d) its lumped equivalent circuit.

**Figure 4** (a) Magnitude and phase plot of conventional and (b) MCSRR.
where \( \eta \) is the refractive index, \( Z \) is impedance, \( \epsilon \) and \( \mu \) represent permittivity and permeability, respectively, \( d \) is the separation between the two rings, \( K \) is the wave vector and \( C \) is the free space velocity of light.

The response curve in Figure 5(a) shows the negative value of \( \eta \) and \( \epsilon \) at the resonating frequency of 2.4 GHz. Figure 5(b) shows the magnitude and phase response of the MCSRR unit cell, which indicates metamaterial property.

By applying the procedure as described in [18, 19], the lumped circuit parameters are extracted. The extracted parameters are as follows: \( L = 8 \) nH, \( C c = 1 \) pF, \( L s = 2 \) nH, \( C s = 2 \) nH, \( R = 1 \) kΩ and \( M = 0.848 \) nH. The mutual inductance, \( M \), has been optimized to get the best result. Keysight ADS circuit simulator has been used to simulate the lumped EC with all the extracted values and the result is plotted in Figure 5(b).

5 | DESIGNING OF MINIATURIZED MARCHAND BALUN

Design of MB starts with cascading of two coupled lines of electrical length \( \theta_c = \lambda/4 \) and coupling coefficient of \( Cc = 0.707 \). These two coupled lines are connected with an uncoupled line of length \( \theta_u \) as plotted in Figure 6(a). Along with that, two CSRR unit cells have been etched in the ground plane, which helps achieve the desired coupling value of the coupled line while reducing the length of the line and transforms the structure into a slow-wave structure, which helps in BW enhancement.

The scattering (S) matrix of an ideal coupled transmission line can be expressed as [20]:

\[
S_c = \begin{bmatrix}
0 & B & A & 0 \\
B/C & 0 & 0 & A/C \\
A/C & 0 & 0 & B/C \\
0 & A/C & B/C & 0
\end{bmatrix}
\]  

(6)

where

\[
A = jC_c \sin \theta_c 
\]  

(7)

\[
B = \sqrt{1 - C_c^2} 
\]  

(8)

\[
S_1 = \frac{B^2 + A^2}{C(A^2 + C^2)} \begin{bmatrix}
A & AB \\
A & AB \\
A & AB \\
A & AB \\
\end{bmatrix} \quad (10)
\]

\[
S_2 = \frac{B^2 + A^2}{C(A^2 + C^2)} \begin{bmatrix}
A^2 & B^2 + BC^2 - A^2B \\
A^2 & B^2 + BC^2 - A^2B \\
A^2 & B^2 + BC^2 - A^2B \\
A^2 & B^2 + BC^2 - A^2B \\
\end{bmatrix} \quad (11)
\]

The S-matrix of the uncoupled transmission line is:

\[
S_3 = \begin{bmatrix}
0 & e^{-j\theta_u} \\
e^{-j\theta_u} & 0
\end{bmatrix} \quad (12)
\]
Since the balun structure is the cascade connection of all the three sections, to deduce the $S$-matrix of the balun, it must multiply the $S$-matrix of these sections.

\[
S_b = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\]  

(13)

where

\[
S_{11} = \frac{A^4 e^{-2j\theta_c} - B^4 - B^2 C^2}{C^2 (B^2 + C^2)}
\]  

(14)

\[
S_{22} = \frac{A^2 B^6 e^{-2j\theta_c} - A^2 B^2 - A^2 C^2}{C^2 (B^2 + C^2)}
\]  

(15)

\[
S_{33} = -\frac{A^2}{B^2 + C^2}
\]  

(16)

\[
S_{12} = S_{31} = \frac{A^3 B e^{-2j\theta_c} - ABC^2 - AB^3}{C^2 (B^2 + C^2)}
\]  

(17)

\[
S_{13} = S_{32} = \frac{(AB^3 - A^3 B + ABC^2) e^{-j\theta_c}}{C^2 (B^2 + C^2)}
\]  

(18)

\[
S_{23} = S_{32} = \frac{(B^4 - A^2 B^2 + B^2 C^2) e^{-j\theta_c}}{C^2 (B^2 + C^2)}
\]  

(19)

These $S$-parameters are the function of the length of the coupled line, $\theta_c$ and uncoupled line, $\theta_u$. A balun designed without an uncoupled line is of $\theta_u = 0$.

For an ideal balun, the following conditions need to be satisfied, $S_{11} = 0$, $S_{33} = -S_{31}$ [21], that is, a fully matched unbalanced port and the power level at both the balanced port must be the same with $180^\circ$ phase shift for all values of $C_c$ and $\theta_c$. Figure 7 shows the amplitude and phase difference variation for different values of $\theta_c$ and $\theta_u$. It is clear from Figure 7(a) and (b) that for a fixed value of $\theta_u$, increasing $\theta_c$ decreases $S_{12}$ and $S_{13}$ amplitude levels. For longer length $\theta_c$ also, amplitude decreases, which results in low BW of the balun. By taking the compromisation between them, the best performance obtained at the optimized length $\pi/5$ for both of $\theta_u$ and $\theta_c$, that is, uncoupled line length is 12.8 mm and coupled line length of 13.06 mm.

The lumped-EC model for the proposed MB [22, 23] is shown in Figure 6(b). The circuit design is carried out in the Keysight ADS circuit simulator. Each section of the proposed MB in Figure 6(a) is well highlighted in Figure 6(b). The L-C equivalent of two quarter-wave coupled lines [24] is connected with an uncoupled line. The lumped-EC of MCSRR units, as
shown in Figure 3(d), is connected in parallel with the coupled line. Hence, mutual inductance is also considered between the quarter-wave coupled line and CSRR cell, denoted by ‘M’. All the lumped component values are optimized at the operating frequency of 2.4 GHz, which is shown in Figure 6(b). Here the value of ‘M’ is considered as 0.505 nH. The circuit simulation result is shown in Figure 9(a).

Two rectangular pads have been connected with the balanced ports to match the impedance to 50 Ω. It is achieved through step impedance matching technique by the cascade connection with a transmission line of dimension 0.8 × 3.56 mm². Figure 8 shows the plot of magnitude and phase response with the variation of width (for fixed-length) of the rectangular pad for the coupled line’s optimized length and uncoupled line. The best result is obtained for the dimension of 4.1 mm width of the rectangular pad.

The simulated magnitude and phase responses of the conventional MB (Figure 1(a)), modified MB without CSRR cells are plotted in Figure 9(a) and (b), respectively, and the proposed MB with CSRR cells (Figure 1(b)) is plotted in Figure 10. The numerical values of all the response curves are tabulated in Table 1. The conventional MB, designed using a planer microstrip line at 2.4 GHz, cannot provide the desired response at the operating
frequency. To achieve the desired response, conventional MB is modified. A ‘U’-shaped uncoupled line is introduced to connect two quarter-wave coupled lines that help achieve the desired phase difference of 180° between two balanced ports shown in Figure 9(b). Two modified and optimized CSRR cells in the ground plane produce a transmission zero at the operating frequency. Two rectangular pads based on step impedance technique in the balanced port and CSRR cells help get the desired magnitude response.

Table 1 shows the comparison between traditional MB’s simulated results, modified MB without CSRR and proposed MB with CSRR. It is evident from this comparison that with the introduction of CSRR cells in the ground plane, enhanced performance is achieved compared to conventional MB and balun without CSRR cells.

6 | RESULTS AND DISCUSSION

The proposed design, depicted in Figure 2, is simulated using HyperLynx 3D EM Designer and measurement has been carried out in Rohde & Schwarz ZNB20 vector network analyzer at 2.4 GHz operating frequency. The FR4 double-sided substrate (substrate height = 1.59 mm, loss tangent = 0.02, dielectric constant = 4.4) has been used to fabricate the proposed design. The simulated result and measured result have been plotted in Figure 10. The lumpedEC, simulated and measured results are tabulated in Table 2 as follows:

The simulated return loss is −38.86 dB, which is well below the −10 dB level from 2.1 GHz to 2.55 GHz and it covers an FBW of 18.75%. Insertion loss is also within this frequency band for 1 dB magnitude deviation with almost equal power division in the balanced ports. The phase deviation between them is 0.85°. Measured results show slight variation from the simulated result due to an imperfect connector connection with the circuit board. The fabricated Marchand Balun using FR4 substrate material is shown in Figure 11.

7 | PERFORMANCE COMPARISON

Table 3 shows a comparison between the proposed work and the existing work.

In [6], the authors achieved an FBW, which is higher than the proposed work but at the cost of a higher circuit area. Phase imbalance was also higher. In another work [7], a smaller circuit area and higher BW was achieved, but costly substrate material was used. The authors in [25] designed a balun using different configurations of 90° coupled transmission lines using costly substrate material. Phase imbalance is also high. In [26], a more miniaturized circuit and increased BW were achieved with two identical coupled transmission-line sections of length smaller than 90°, few lumped elements and an isolation circuit. But its performance degrades in terms of magnitude and phase imbalance in the balanced ports. The balun at 2.4 GHz and which was designed in [23] using the FR4 material utilised interdigital based transmission line that suffers from higher phase imbalance compared to the proposed work.

| Parameters                  | Traditional MB (using microstrip line at 2.4 GHz) | Modified MB without CSRR | Proposed MB with CSRR |
|-----------------------------|---------------------------------------------------|--------------------------|------------------------|
| dB[S(1,1)]                  | −2.75                                             | −2                       | −38.86                 |
| dB[S(1,2)]                  | −10.09                                            | −9.21                    | −3.39                  |
| dB[S(1,3)]                  | −7.91                                             | −10.45                   | −3.56                  |
| Phase difference, Ang[S(1,3)] - Ang [S(1,2)] | −1.23°                                           | −180.96°                 | −180.85°               |
TABLE 2  Lumped equivalent circuit, simulated and measured result of the proposed Marchand balun

| Parameters | Lumped equivalent circuit | Simulated | Measured |
|------------|---------------------------|-----------|----------|
| dB[S(1,1)]| −24.061                   | −38.86    | −32.24   |
| dB[S(1,2)]| −3.025                    | −3.39     | −3.75    |
| dB[S(1,3)]| −3.538                    | −3.56     | −3.82    |
| Phase difference, Ang[S(1,3)] - Ang[S(1,2)] | −181.38° | −180.85° | −178.55° |

TABLE 3  Performance comparison of proposed Marchand balun

| References | Design technique | Design frequency (GHz) | Substrate material used | Circuit size ($\lambda_g \times \lambda_d$) | FBW (%) | Magnitude imbalance (dB)/phase imbalance (degrees) | Return loss ($S^H$) in dB |
|------------|------------------|------------------------|-------------------------|---------------------------------|---------|-------------------------------------------------|--------------------------|
| [6]        | Based on broadband coupled line power divider and an improved phase shifter, which incorporates coupled-line and composite right/left-handed transmission lines | 2.75 | Not mentioned | 1.352 × 0.754 | 88.7 | 0.5/10 | ~ −34.5 |
| [7]        | By using meander branched branch-line coupler and a quarter-wavelength stub at the upper right corner of the conventional branch-line balun | 1.5 | RT Duroid 6006 substrate | 0.197 × 0.197 | 37.9 | 0.5/10 | ~ −20 |
| [25]       | 90° coupled transmission-line sections | 2 | RT Duroid 5870 | Not mentioned | Not mentioned | 0.45/2.78 | −15.78 |
| [26]       | With the help of two identical coupled transmission-line sections of length smaller than 90°, few lumped elements and an isolation circuit | 0.7 | RT Duroid 5870 | 0.123 × 0.031 | 40 | 0.65/1.2 | −34.2 |
| [23]       | Using interdigital capacitor-based transmission line | 2.4 | FR4 | 0.51 × 0.22 | 37.5 | 0.415/5.48 | −26.23 |
| This study | Introduction of an uncoupled line to connect two coupled line and two CSRR unit cell at the ground plane | 2.4 | FR4 | 0.515 × 0.279 | 18.75 | 0.56/0.85 | −38.86 |

8  | CONCLUSION

A miniaturized MB is proposed which occupies a circuit area of $0.515 \times 0.279 \lambda_g$ with enhanced FBW of 18.75% operating at 2.4 GHz frequency. To enhance the circuit performance, two CSRR unit cells have been etched in the ground plane, which behave like negative dielectric constant material. This proposed MB is fabricated on a low-cost FR4 substrate which gives a very good result at the operating frequency. For validation, the simulated results are compared with the measured result. It is determined that there they maintain a good agreement with each other.
ACKNOWLEDGEMENT
The author wants to acknowledge the Indian Space Research Organization (ISRO) for their support and Mr Dipesh Deb Nath, Lab technician, NIT Agartala, for helping in the fabrication process.

ORCID
Partha Kumar Deb https://orcid.org/0000-0001-6722-8737

REFERENCES
1. Pozar, D.M.: Microwave Engineering, 4th ed. Wiley, New York (2011)
2. Bower, R., Wolfe, J.J.: A printed-circuit Balun for use with spiral antennas. IRE Trans. Microw. Theory Tech. 8, 319–325 (1960)
3. Hallford, B., R.: A designer's guide to planar mixer baluns. Microwaves. 18, 52–57 (1979)
4. Bassett, R.: Three Balun designs for push-pull amplifiers. Microwaves. 19, 47–52 (1980)
5. Marchand, N.: Transmission-line conversion transformers. Electronics. 17, 142–146 (1944)
6. Yongle, W., et al.: A compact planar wide-band balun with high isolation based on coupled-line and composite right–left-handed transmission line. Microw. Opt. Technol. Lett. 58, 372–376 (2016)
7. Li, J.L., Qu, S.W., Xue, Q.: Miniaturised branch-line balun with bandwidth enhancement. Electron. Lett. 43, 931–932 (2007)
8. Guo, Y-X., et al.: A novel LTCC miniaturized dual band balun. IEEE Microw. Wirel. Compon. Lett. 16, 143–145 (2006)
9. Tseng, C., Hsiao, Y.: A new broadband Marchand balun using slot-coupled microstrip lines. IEEE Microw. Wirel. Compon. Lett. 20, 157–159 (2010)
10. Pickartz, I., et al.: Compact single-layer microstrip Marchand type balun. IEEE 16th Annual wireless and microwave technology conference (WAMICON), pp. 1–4, Cocoa Beach, FL (2015)
11. Shie, C., et al.: A Miniaturized microstrip balun constructed with two λ/8 coupled lines and a redundant line. IEEE Microw. Wirel. Compon. Lett. 20(12), 663–665 (2010)
12. Keshavarz, S., Nozhat, N.: Dual-band Wilkinson power divider based on composite right/left-handed transmission lines. 13th International conference on electrical engineering/electronics, computer, telecommunications and information technology (ECTI-CON), Chiang Mai, pp. 1–4 (2016)
13. Keshavarz, S., et al.: Design and implementation of low loss and compact microstrip triplexer using CSRR loaded coupled lines. AEU-Int. J. Electron. Commun. 152913(111), 1–5 (2019)
14. Shelby, R.A., Smith, D.R., Shultz, S.: Experimental verification of a negative index of refraction. Science. 292(5514), 77–79 (2001)
15. Veselago, V.G.: The electrodynamics of substances with simultaneously negative value of ε and μ. Soviet Physics Uspekhi. 10(4), 509–514 (1968)
16. Pendry, J.B.: Negative refraction. Contemp. Phys. 45(3), 191–202 (2004)
17. Smith, D.R., et al.: Electromagnetic parameter retrieval from inhomogeneous metamaterials. Phys. Rev. E. 71(3), 1–11, 71036617 (2005)
18. Caloz, C., Itoh, T.: Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications. Wiley, Hoboken (2006)
19. Náqui, J., Duran-Sindreu, M., Martin, F.: Modeling split-ring resonator (SRR) and complementary split-ring resonator (CSRR) loaded transmission lines exhibiting cross-polarization effects. IEEE Antennas Wirel. Propag. Lett. 12, 178–181 (2013)
20. Li, C., Liu, K., Li, F.: An equivalent circuit for the complementary split ring resonators (CSRRs) with application to highpass filters. International symposium on Biophotonics, Nanophotonic and Metamaterials, Hangzhou, pp. 478–479 (2006)
21. Xu, L., Wang, Z., Li, Q.: Design and analysis of millimeter-wave Marchand balun with interconnected transmission line. J. Infrared Millim. Terahertz Waves. 30, 738–745 (2009)
22. Joyansen, T., Krozer, V.: Analysis and design of lumped element Marchand baluns. IEEE Trans. Microw. Theory Tech. 65(3), 746–760 (2017)
23. Ahn, H.R., Tentzeris, M.M.: Novel generic asymmetric and symmetric equivalent circuits of 90° coupled transmission-line sections applicable to Marchand Baluns. IEEE Trans. Microw. Theory Tech. 65(3), 746–760 (2017)
24. Carey-Smith, B.E., et al.: Wide tuning-range planar filters using lumped-distributed coupled resonators. IEEE Trans. Microw. Theory Tech. 53(2), 777–785 (2005)
25. Johansen, T., Krozer, V.: Analysis and design of lumped element Marchand baluns. In: MIKON 2008 - 17th International conference on microwaves, radar and wireless communications, pp. 1–4. Wrocław (2008)
26. Kumari, A., Bhowmik, P., Moyna, T.: Design and validation of miniaturize rat race coupler based microstrip Balun. AEU–Int. J. Electron. Commun. 95, 155–161002E (2018)

How to cite this article: Deb PK, Moyna T, Bhattacharyya BK. Miniaturized and enhanced bandwidth Marchand balun using CSRR. IET Microw. Antennas Propag. 2021;15:788–796. https://doi.org/10.1049/mia2.12086