A Compact Wideband CSRR Near Zero Refractive Index and Epsilon Negative Metamaterial for Wearable Microwave Applications

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Abstract. A complementary split-ring resonator (CSRR) decagonal shaped textile-based single-negative metamaterial (MTM), considering a frequency range from 1 to 15 GHz, is presented in this paper. Seven different unit cell arrays (i.e., 1×1, 1×2, 1×3, 2×1, 2×2, 1×3 and 3×3) are analysed to evaluate the effects of the unit-cell arrays on the resonance frequencies of the MTM. The designed unit cell arrays exhibit average negative permittivity bandwidth of 12.87 GHz (from 1 to 12.87 GHz) and an average near-zero-refractive-index (NZRI) bandwidth of 11.98 GHz (from 1.015 to 12.995 GHz). Simultaneous negative permittivity and NZRI results at L, S, C, X and Ku frequency bands indicate the proposed MTM is suitable for various wearable applications in these frequency regimes.

Keywords: Metamaterial, wideband metamaterial, complementary split ring resonator (CSRR), near-zero refractive index (NZRI), ENG metamaterial.

1. Introduction

Any material can be represented electromagnetically by means of permittivity (ε) and permeability (μ). One of the essential material parameters, which depends more on ε and μ, is the refractive index (η). η determines the refraction and reflectivity in each material. Metamaterials (MTM) are artificially created material that may have either negative ε or μ or simultaneously negative[1,2]. According to ε and μ results, the MTMs can be divided into four groups. The materials with positive ε and μ values are classified as double positive (DPS) which generally found in nature. The MTM with either negative ε or negative μ value is classified as Single negative (SNG) MTM[3]. Epsilon-negative (ENG) and mu-negative (MNG) materials are categorised under SNG MTM [4]. If a MTM has negative ε and
positive $\mu$, is known as ENG MTM. On the other hand, if the MTM’s $\mu$ is negative with positive $\varepsilon$ is known as MNG MTM. For the double negative (DNG) material, both $\varepsilon$ and $\mu$ should be negative. DNG MTM also has negative refractive index that is not found in nature, resulting in unique properties [5]. Researchers are using MTMs for a variety of applications, including wireless health monitoring [6], invisibility cloaking [7], filters [8] and RFID Tag [9]. Planar patterns and capacitance-loaded strips (CLs) [10], complementary split-ring resonators (CSRRs) [11], split-ring resonators (SRRs) [2], and electromagnetic bandgap (EBG) structures [12] are the various forms of MTMs proposed in different works.

This paper presents a CSRR decagonal shaped textile MTM design that exhibits wideband (i.e., average bandwidth over 12 GHz) of ENG and near-zero-refractive-index (NZRI) properties for seven different array conditions. Section 2 gives a detailed approach to design the proposed MTM. Section 3 describes the detailed analysis of the MTMs parameter extraction technique. Section 4 explains the results and analysis. The study is eventually concluded in section 5.

2. Metamaterial Unit Cell Construction

In this work, ShieldIt Super™ is used as the conductive textile, while felt material is as the dielectric substrate. The dielectric constant of the 3mm felt used in this work is 1.44, with a loss tangent of 0.044. As for the ShieldIt, the conductivity is $1.18 \times 10^5$ S/m and the thickness is 0.17 mm.

Figure 1 shows the proposed MTM unit cell in this study, while Figure 2 outlines the process to construct the proposed unit cell. The first step starts with the construction of two different outer and inner decagonal shapes splits. Then the exterior form has been rotated 90° degrees in the second step. Followed by the remainder steps, a decagonal SRR is formed step 6. In step 7, the SRR shape from the proceeding step is subtracted from $8 \times 8$ mm² conductive material to create the proposed CSRR shape. All parameters involved in this study are tabulated in Table 1.

![Figure 1. MTM unit cell ($1 \times 1$ array). (a) front view. (b) rear view (c) 3D view.](image-url)
3. Methodology
The MTM structure and electromagnetic wave interaction yield various characteristics. The unit cell is positioned at the z-axis direction between two waveguide ports. Figure 3 shows boundary conditions of the MTM unit cell considering a perfect magnetic conductor (PMC) at the y-axis and a perfect electric conductor (PEC) at the x-axis; thus, a transverse electromagnetic (TEM) wave is generated. Simulation is carried out utilising the available frequency-domain solver in CST. A frequency between 1 and 15 GHz has chosen to characterise the MTM unit cells. A similar setup is applied to the $1 \times 2$, $1 \times 3$, $2 \times 1$, $2 \times 2$, $1 \times 3$ and $3 \times 3$ unit cell arrays for MTM characterisation.

To retrieve effective parameters (i.e., $\varepsilon$ and $\mu$) from the reflection coefficient ($S_{11}$) and transmission coefficient ($S_{21}$), the robust reflection transmission (RTR) method is applied [13], [14]. The MTM effective parameters are retrieved using equations (1) to (7) as follows,

Table 1. Dimensions of the Proposed MTM Unit Cell

| Parameter | Value(mm) | Parameter | Value(mm) |
|-----------|-----------|-----------|-----------|
| L         | 8         | g1        | 0.5       |
| W         | 8         | g2        | 0.6       |
| R1        | 2.9       | d         | 0.5       |
| R2        | 2.2       | h         | 3         |
| R3        | 1.7       | t         | 0.17      |
| R4        | 1.2       |           |           |

Figure 2. The schematic diagram and how the proposed unit cell evolved.
\[ S_{11} = \frac{R_{01}(1 - e^{2ik_0d})}{1 - R_{01}^2 e^{2ik_0d}} \]  \hspace{1cm} (1)

\[ S_{21} = \frac{(1 - R_{01}^2)e^{ink_0d}}{1 - R_{01}^2 e^{2ink_0d}} \]  \hspace{1cm} (2)

where \( k_0 \) = the wave vector in free space, \( d \) = prototype/slab thickness, \( n \) = refractive index, \( R_{01} = \frac{z - 1}{z + 1} \) and \( z \) = impedance. Solving (1) and (2) outcomes in (3):

\[ z = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \]  \hspace{1cm} (3)

\[ e^{ink_0d} = X \pm i\sqrt{1 - X^2} \]  \hspace{1cm} (4)

where \( X = \frac{1}{2S_{21}(1 - S_{11}^2 + S_{21}^2)} \)

\[ n = \frac{1}{k_0 d} \left[ \text{imaginary}(\ln e^{ink_0d}) + 2m\pi \right] - i\left[ \text{real}(\ln e^{ink_0d}) \right] \]  \hspace{1cm} (5)

where \( m \) = an integer value of branch index complexity [15]. Additionally, \( \varepsilon \) and \( \mu \) are calculated using (6) and (7), respectively, as follows,

\[ \varepsilon = \frac{n}{z} \]  \hspace{1cm} (6)

\[ \mu = nz \]  \hspace{1cm} (7)

4. Result and Discussion

The surface current distributions are analysed and discussed at distinct frequencies to investigate the proposed metamaterial behaviour and understand the physical phenomena in which it functions when it is situated in an electrical and magnetic field region. Figure 4 shows the surface current distribution...
of the proposed MTM unit cell at 1.5 GHz, 3 GHz, 5 GHz, 9 GHz and 12.5 GHz. The arrows show the current distribution direction in the overall structure, and colours indicate the current intensity. The incident waves stimulate circulating currents along the CSRR decagonal-shaped, giving rise to \( \mu \) moments of a magnetic dipole. The attraction of electric dipoles would also result in increased electrical interaction. More intense surface current realised at 1.5 GHz, 3 GHz, 5 GHz and 12.5 GHz compared with 9 GHz.

The proposed textile-based MTMs simulated transmission coefficient \( S_{21} \) is shown in Figure 5. Slight discrepancies in terms of the \( S_{21} \) results have investigated for \( 1 \times 1, 1 \times 2, 1 \times 3, 2 \times 1, 2 \times 2, 3 \times 1 \),

**Figure 4.** Surface current distributions at different operating frequencies.

**Figure 5.** \( S_{21} \) results for different unit cell arrays.
and $3 \times 3$-unit cell array conditions. The $S_{21}$ has a bandwidth of about 12.05 GHz (from 1 to 13.05 GHz) for all unit cell array conditions.

Figures 6 and 7 demonstrate $\varepsilon$ and refractive index results for each unit cell arrays, respectively. As summarised in Table II, similar results obtained regardless of the different unit cell array conditions. Moreover, the ENG and NZRI results indicate adequate bandwidth within the L-band, S-band, C-band, X-band and Ku-band.

Figure 6. The permittivity ($\varepsilon$) values for different unit cell arrays.

Figure 7. The refractive Index ($\eta$) results for different unit cell arrays.
5. Conclusion
A textile-based unit-cell MTM structure and corresponding array configurations are designed and analysed in this paper. Over a frequency between 1 and 15 GHz, the effective parameters and $S_{21}$ of the proposed MTM is investigated. The findings indicate SNG metamaterial characteristics with wideband frequency bands in different unit cell arrays across the range. The unit cell exhibits the ENG and NZRI characteristics at microwave frequencies of L, S, C, X and Ku bands. It also found that while considering bigger MTMs size (i.e., in terms of array conditions), the negative MTM characteristics migrate towards lower frequencies resulting in greater bandwidth. Besides that, compact size of the MTM and reasonable $S_{21}$ results makes the MTM suitable for current textile-based radio, satellite, and cellular communication applications.

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