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Negative refraction metamaterial with low loss property at millimeter wave spectrum

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Article Info

ABSTRACT

The design of the millimetre-wave (MMW) metamaterials (MMs) unit cell operates at 28 GHz is presented and numerically investigated. The proposed structure composed of a modified split ring resonator (MSRR) printed on both sides of the substrate layer. Popular MM structures such as S-shape, G-shape, and Ω-shape are adjusted to operate at the 28 GHz for comparison purpose. MSRR achieves a wide bandwidth of 1.1 GHz in comparison with its counterparts at the resonance frequency. Moreover, the proposed structure presents very low losses by providing the highest transmission coefficient, S_{21}, at the corresponding frequency region. The radiation loss is substantially suppressed and the negativity of the constitutive parameters of the proposed MM structure is maintained. By applying the principle of the electromagnetically induced transparency (EIT) phenomenon, the MSRR unit cell induces opposite currents on both sides of the substrate which leads to cancelling out the scattering fields and suppresses the radiation loss. The constitutive parameters of the MM structures are retrieved using well-known retrieval algorithm. The proposed structure can be used to enhance the performance of fifth-generation (5G) antenna such as the gain and bandwidth.

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1. INTRODUCTION

Metamaterials (MMs) are engineered materials with an extraordinary property not usually found in nature such as the negative permittivity ε, permeability, μ and the refractive index, n [1]. These unique properties were predicted theoretically in 1967 by the Russian scientist Victor Veselago. After 29 years, the experimental verification of the negative ε and μ had been introduced by Pendry in 1996 [2-3]. Subsequently, different types of artificial MMs unit cells with different shapes had been introduced, such as the SRRs [4], complementary CSRRs [5], broad-side-coupled SRRs [6], fishnet structure [7], Ω-shape [8]. G-shape [9] and S-shape [10]. MMs with unique electromagnetic properties had been proposed for a wide range of applications. However, these artificial materials suffer from serious impairments that restrict their range of applications and late enable MM based devices such as tight bandwidth and the losses. MM suffers from high losses when the operating frequency is increased to the higher range such as in the MMW

frequency range [11]. These inherent losses can introduce a serious problem in losing the unusual electromagnetic properties of the MMs. MMs losses are induced by radiation and ohmic losses [12]. The radiation loss is the major component of losses in the MMs [13]. In this regard, low loss MMs structures are in high demand to integrate the MMs with practical devices, especially at high-frequency range. In the literature, various techniques had been proposed to compensate the MMs losses at different frequency bands. For example, using the RLC resonance circuit model of the MMs structures to reduce the losses by increasing quality factor (Q- factor) value and thereby compensate the MMs losses [14], tailoring geometry of MM unit cell [15, 16], and integrate gain materials or active devices with MM unit cell [17]. The most common technique is using the electromagnetically induced transparency phenomenon (EIT). This method provides low loss and maintains the negativity of constitutive parameters of the MMs structures [18-20]. On the other hand, the large swathes of the spectrum, high speed and high channel capacity offered by MMW frequency range make this spectrum appropriate option for different applications like automotive radars, Gbit communications, and medical imaging sensors [21-23]. Recently, the MMW frequency range is proposed for future 5G communications. The tremendous available amount of MMW band is utilized to increase the capacity of the communication system [23].

In this paper, the MSRR MMs unit cell that operates at the MMW frequency range is designed and numerically investigated. For comparison purposes, three common MMs structures which are the S-shape, G-shape, and Ω-shape are optimized to operate at 28 GHz. The proposed MM structure shows a very high performance than its counterparts at the corresponding frequency region by providing the highest transmission coefficient, S21. In addition, the negativity of the constitutive parameters of the MM structures is maintained at the specified frequency range.

2. THE PROPOSED MM STRUCTURE

The schematic view of the proposed MSRR, S-shape, G-shape, and Ω-shape unit cells are illustrated in Figure 1(a)-(d). The double split ring metallic shapes of the MSRR structure are printed on both sides of the substrate. The proposed MSRR structure and other known unit cells are constructed onto Rogers RT5880 substrate with the dielectric constant of 2.2, tangent-loss of 0.0009, and thickness of 0.508 mm. The metallic layer is the lossy metal copper with a conductivity of 5.8×10^7 S/m and the thickness of 0.035 mm. The dimensions of the structure are L=2 mm, W=2 mm, L1=1.8 mm, W1=1.9 mm, L3=0.9, G=0.1 mm. The length (L) and width (W) of other unit cells are given in the caption of Figure 1. The boundary conditions are applied to induce the electromagnetic wave (EM) and to retrieve the permeability, permittivity and refractive index of the MSRR MM structure. In this work, the electric field and magnetic field are assigned along the y-axis and x-axis, respectively. The electromagnetic wave is guided through the z-direction. The CST Microwave Studio is used to perform the numerical simulation.
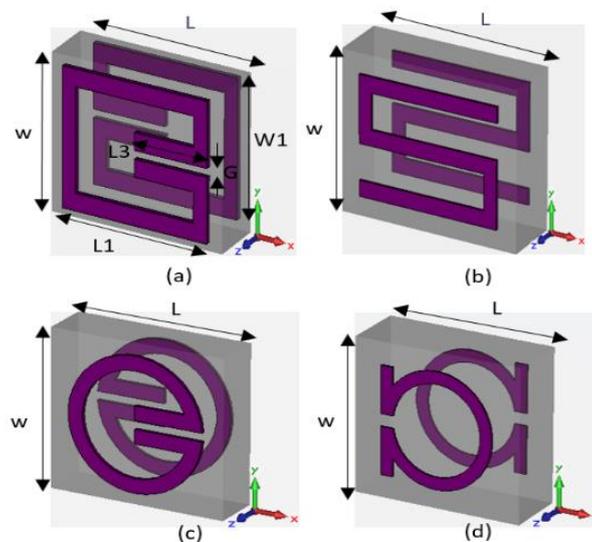

Figure 1. The schematic view of the MM structures, (a) The proposed MSRR,
(b) S-shape (2×2.9 mm), (c) G-shape (2×2.3 mm), (d) Ω -shape (4×3.7 mm)

3. S-PARAMETERS PERFORMANCE

The proposed MSRR, S-shape, G-shape, and Ω-shape unit cells are designed and adjusted to operate at 28 GHz. The reflection coefficients, S_{11}, of the proposed MSRR and the other three-unit cells are depicted in Figure 2. At 28 GHz, the MSRR structure realize the best performance in terms of reflection coefficient and bandwidth over other MM structures. This structure achieves a reflection coefficient of -36 dB and the bandwidth of 1.1 GHz. The lowest bandwidth is achieved by the S-shape unit cell with a bandwidth of 0.2 GHz. In terms of bandwidth, the proposed MSRR unit cell presents a wider bandwidth as compared to the other unit cells in spit of the drawback of the tight bandwidth of MMs.
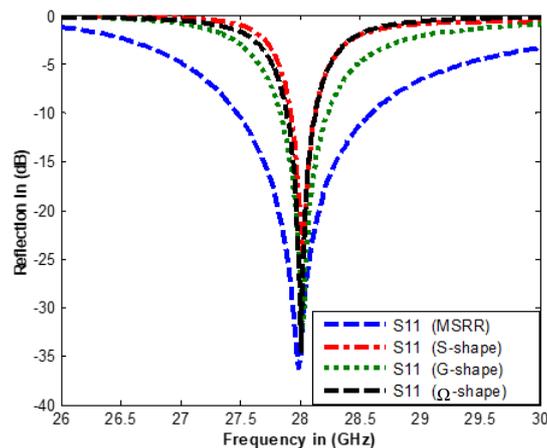

Figure 2. Simulated reflection coefficient results of the proposed MSRR, S-shaped, G-shape, and Ω-shape unit cells

The MMs losses turn out to be a serious issue which limits their practical applications, especially at the MMW spectrum. To reduce the inherent loss in the MMs, the radiation loss should be suppressed. In this subsection, the dominant component in the MM losses, radiation loss, of the MSRR and the other three MM unit cells are analyzed, investigated and minimized at 28 GHz. The transmission coefficient of the proposed MSRR, S-shape, G-shape, and Ω-shape unit cells at 28 GHz are plotted in Figure 3. It is noticeable that the loss achieved by MSRR unit cell is very small in comparison with its counterparts where it achieves -0.1 dB. This low loss achievement is due to tailoring the parameters of the structure at the simulation stage. The highest loss is presented by S-shaped resonator with approximately -0.5 dB. In order to understand the reduction mechanism of the MM radiation loss, the induced surface current distribution based on the electromagnetically induced transparency (EIT) phenomenon is used.
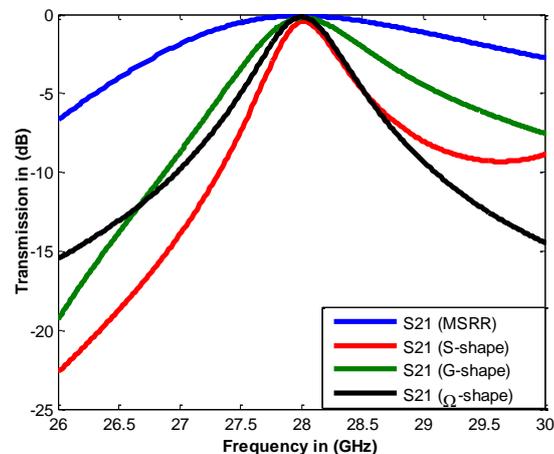

Figure 3. Simulated transmission coefficient results of the proposed MSRR, S-shaped, G-shape, and Ω -shape unit cells

The induced surface currents of the MSRR structure and other unit cells at 28 GHz are depicted in Figure 4. The induced surface current of the MSRR structure produces a circulating current on the front and back sides of the unit cell through the strip that extends to the middle of the structure which leads to the magnetic dipole response as shown in Figure 4(a). However, due to the excitement of the magnetic dipole response, the electric dipole response is also simultaneously excited, which leads to induce significant radiation losses. By applying the opposite currents through the double rings on both sides of the substrate, where one of the double rings is the inverse of the other, the induced currents cancel out on both sides of the structure, subsequently suppressing the radiation loss. In specific, the modification in the unit cell parameters through the simulation display the antiparallel currents at both sides of the unit cell which lead to cancelling out the scattering fields on both sides, thus induces the EIT effect and greatly suppresses the radiation loss. Moreover, one can observe that the surface current distribution of the MSRR is fully uniform over the whole MM structure, which supports the low loss attribute of the MM structure [11].

The induced current of the S-shape unit cell is not uniform over both sides as compared to the MSRR structure, thereby the loss is extremely high. The electric dipole moment is introduced by the horizontal lines of the S-shape, subsequently increasing the radiation loss of this structure as shown in Figure 4(b). The low loss mechanism of MSRR can be applied for G-shape unit cell where the currents on both sides of the G-shape cancel out each other and thereby reducing the radiation loss as depicted in Figure 4(c). The loss of this structure is relatively low in comparison to S-shape unit cells. However, the surface currents are not sufficiently uniform over the whole structure and this introduces a bit high loss as compared to our proposed structure. The surface current distribution is uniform over the Ω-shape structure as shown in Figure 4(d). Thus the loss is low in comparison with S-shape.
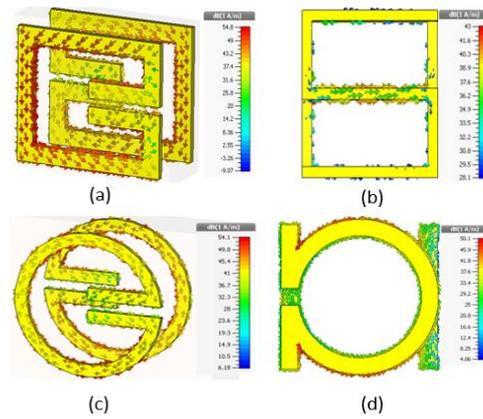

Figure 4. The induced surface current of both sides of the unit cells at 28 GHz, (a) the proposed MSRR, (b) S-shape, (c) G-shape, (d) Ω -shape

4. RETRIEVE THE CONSTITUTIVE PARAMETERS

The properties of the four MM structures such as complex reflection and transmission have been extracted using CST microwave studio. Then the constitutive parameters can be retrieved using a well-known algorithm which is a robust method [24]. In this algorithm, the properties of the four structures which extracted from the simulation are used to calculate the index of refraction, n_{eff} and impedance z_{eff}. The relation between the s-parameters and the effective impedance, z_{eff} is given by:

$$s_{11} = \frac{R_Z(1 - e^{i2nkd})}{1 - R_Z^2 e^{i2nkd}} \tag{1}$$

$$s_{11} = \frac{(1 - R_Z^2)e^{i2nkd}}{1 - R_Z^2 e^{i2nkd}} \tag{2}$$

where $R_Z = z-1/z+1$, k_0 and d are the wavenumber and the thickness of the MM structure, repectively. By inverting (1) and (2), the z_{eff} and n_{eff} are obtained based on the S-parameters as follows [25]:

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

$$n_{eff} = \frac{1}{kd}[\{Img(\ln(e^{inkd})) + 2m\pi\} - iRe(\ln(e^{inkd}))] \qquad (4)$$

where,

$$e^{inkd} = \left[\left(\frac{1}{2S_{21}}\right)\left(1 - S_{11}{}^2 + S_{21}{}^2\right)\right] \mp$$

$$i\sqrt{1 - \left[\left(\frac{1}{2S_{21}}\right)(1 - S_{11}{}^2 + S_{21}{}^2)\right]^2} \qquad (5)$$

The effective permittivity and effective permeability can be calculated using the following expression:

$$\varepsilon_{eff} = nz \text{ and } \mu_{eff} = n/z \qquad (6)$$

The real parts of the permittivity ε, permeability μ and the refractive index, n of the proposed MSRR, S-shape, G-shape, and Ω-shape unit cells are plotted in Figures 5(a)-(d). As can be seen from Figure, all structures present a negative index of refraction at the resonance frequency with different ranges. The transmission coefficient peaks of the structures in the region where all the real parts of the constitutive parameters are negative. Our proposed unit cell unveils a very large negative refractive indexes bandwidth which extended over the two regions above and below the resonance frequency. The range of the first region, below the resonant frequency, is extended from 23.8 GHz up to 28 GHz and 28.3 GHz up to 29 GHz for the region above the resonance frequency. The negative refractive index of the S-shaped resonator is extended above and below the resonance frequency as well, but with a small range of the negativity. However, G-shape and Ω-shape unit cells introduce a large bandwidth of the negative refractive index either below or above the resonance frequency. The performance of the four MM structures is compared and tabulated in Table 1.
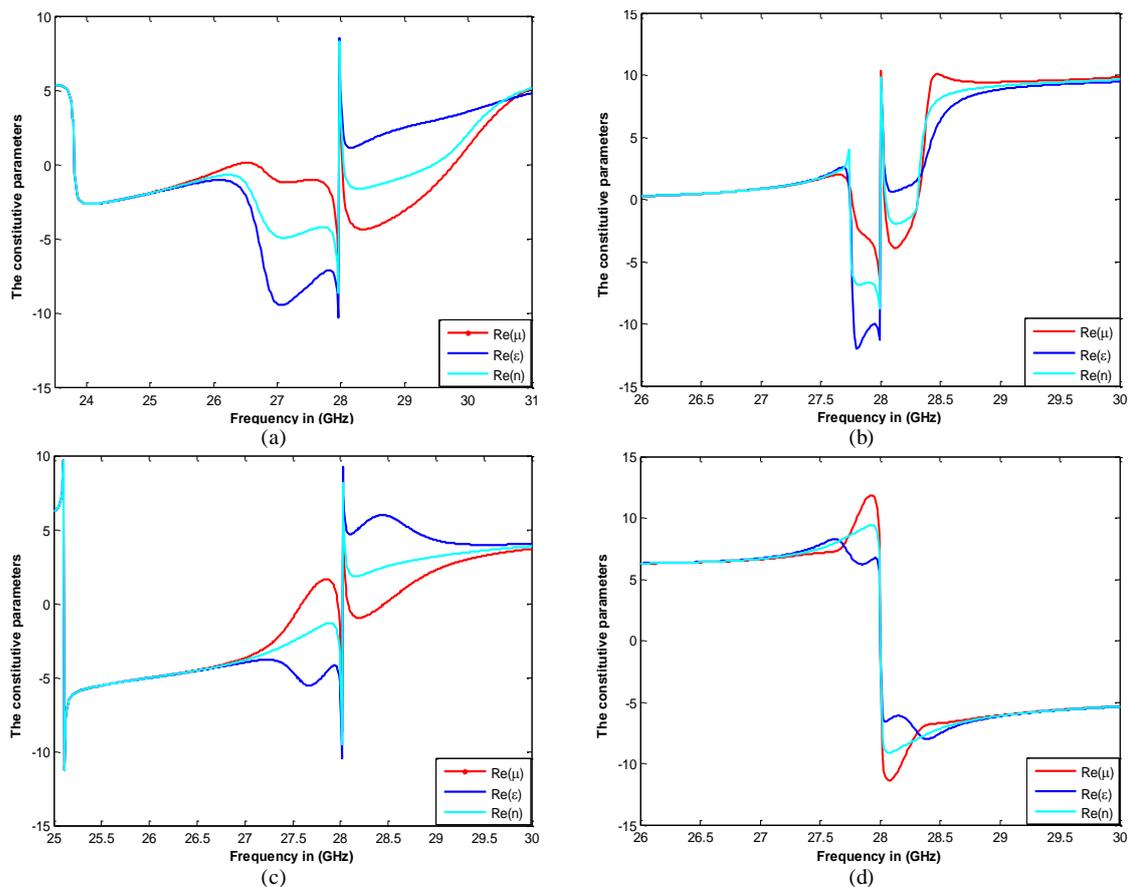

Figure 5. The real parts of the constitutive parameters at 28 GHz, (a) the proposed MSRR unit cell, (b) S-shape, (c) G-shape, (d) Ω -shape

Table 1. The performance comparison of the four MM structures

MM structure	Proposed MSRR	S-shape	G-shape	Ω-shape
S11 (dB)	-36	-24	-32	-34
S21 (dB)	-0.1	-0.5	0.3	-0.2
Bandwidth (GHz)	1.1	0.2	0.4	0.22
Range of negative refraction (GHz)	4.2	0.23	2.85	4

5. CONCLUSION

In conclusion, the low loss MSSR structure operating at MMW frequency range is proposed and numerically characterized. The MSRR is composed of modified double metallic rings printed on both sides of the substrate which operates at 28 GHz. For comparison purpose, S-shape, G-shape, and Ω-shape unit cells are optimized to operate at 28 GHz. Despite the common drawback of the narrow bandwidth of the MMs, the proposed unit cell achieves a wide bandwidth of 1.1 GHz. Moreover, the proposed MM structure shows very high performance in comparison with its counterparts at the resonance frequency by providing the lowest loss, -0.1 dB. EIT phenomenon is induced by modifying the MM structure to apply the opposite currents on both sides of the substrate which lead to cancelling out the scattering fields. Subsequently, the major component of the MMs losses which is the radiation loss is greatly suppressed. Moreover, the surface current distribution of the MSRR is fully uniform over the whole structure, which supports the low loss attribute of the MM structure. The constitutive parameters are extracted using a well-known algorithm and the negative constitutive parameters are maintained at the resonance frequency. The proposed MSRR unit cell displays a wide bandwidth of the negative refractive index which extended above and below the resonance frequency. The proposed structure has been investigated through the simulation. This study recommends as a future work test the same structure through the fabrication and measurement. MSRR structure can be utilized to enhance the gain and bandwidth of 5G antenna.

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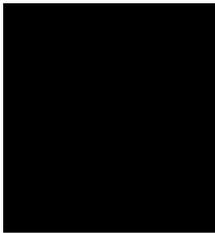
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