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Design and analysis with different substrate materials of a new metamaterial for satellite applications

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Abstract: In this paper, we are presenting a new metamaterial unit cell for satellite applications. The unit cell of the metamaterial was designed on FR-4 substrate material. The transmission characteristics of the unit cell display resonance at the frequency of 3.45 GHz of S-band of microwave region, which is usually suited for satellite communications. We did further analysis on the material's effective medium properties by replacing the substrate material with Rogers RT 6010, lossy polyimide and aluminum nitride substrate materials, and we achieved different promising electromagnetic properties including double negative characteristics within the same band as well. For all these analyses, the popular “CST Microwave Studio” simulation software was adopted. The proposed design gives fine controllability in different types of metamaterial just by changing the substrate material, and all are working in the same S-band microwave spectrum.

Keywords: DNG; metamaterials; satellite; S-band.

1 Introduction

Since the arrival of metamaterial, there has been a growing attention in the scientific community on it. A metamaterial is an artificially constructed material that adopts some unit cells of extraordinary properties. At the

beginning, Victor Veselago proposed a material in 1968 that may display negative permittivity ($\epsilon < 0$) as well as permeability ($\mu < 0$) at a certain frequency [1], but it was not possible naturally. After many years, Smith et al. [2] successfully demonstrated such material with practical experiment. It does display some exotic properties like inverted Snell's law, negative refractive index, etc. Metamaterials are classified depending on the property of permittivity (ϵ) and permeability (μ) of that material, such that, if either of the properties of permittivity (ϵ) or permeability (μ) is negative, then primarily, it is defined as a single negative (SNG) metamaterial. SNG metamaterials are also further classified in two types, namely, ENG (metamaterial with only negative permittivity) and MNG (metamaterial with only negative permeability). Due to these unusual electromagnetic properties of metamaterials, they can be used in many exciting applications, such as designing antenna with desired high gain and directivity, reducing SAR, using in invisibility cloaking, and for increasing photonic absorption rate of solar cell [3–5]. According to the applications, several types of structures for metamaterial unit cell are proposed such as U-shape, V-shape, S-shape, etc. [6, 7]. Islam et al. showed a metamaterial in Ref [4] that works in the X-band only. Ekmekci and Turhan-Sayan in Ref. [7] presented an SNM that works in the X-band only. Soric et al. [8] provided an epsilon near zero metamaterial that was applicable in the L-band only. In Ref. [9], a double negative metamaterial was reported, but it also was designed for C-band only.

A new unit cell structure to form metamaterial is introduced in this paper; each unit cell consists of two complementary split ring resonators (SRRs) with a conductive bar between these rings. With this proposed material, we found resonance in the S-band (2–4 GHz) of microwave frequency spectra, and it appears as a SNG megamaterial. S-band has promising applications in the satellite communications. Besides satellite applications, S-band has many applications in other sectors like Bluetooth, wireless LAN, WiMax communications, etc. This unit cell was simulated using CST microwave simulation

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software. Then its complex scattering parameters are computed, and the resonance frequencies are observed. The value of effective permittivity (ϵ) and permeability (μ) was retrieved from these parameters for the above unit cell. In addition, we have done experiments by changing the substrate material with Rogers RT 6010, aluminum nitride and lossy polyimide instead of FR-4, and we have done the comparative analysis of the results.

2 Design of the unit cell

The schematic views of the proposed unit cell structure with details design parameter are shown in Figure 1. Each unit cell consists of two complementary SRRs, and a rectangular copper bar is placed between these by maintaining 0.5-mm-thick copper layer for all. The inner radius and outer radius of each ring are 3 mm and 4 mm, respectively. The distance of gap is 1 mm. The intermediate rectangular copper bar is designed with a length and width of 14 mm and 1.6 mm, respectively. A 0.33-mm gap is maintained with copper bar from each ring. The whole unit cell is fabricated on a FR-4 substrate with dielectric loss-tangent of 0.002 and dielectric constant of 4.2. The length and width

Figure 1: The structure of proposed unit cell.

of substrate are taken as 30 mm for both with a height of 1.6 mm.

3 Methodology

We used the well-known simulation software CST microwave studio (CST Microwave Studio, CST of America®, MA, USA) in our study. In between positive and negative waveguide ports, the designed structure is placed along x -axis and excitation also applied in the direction of same axis by the electromagnetic wave. In case of boundary declaration, the Y -plane is assigned as the perfect electric conductor (PEC) boundary and the Z -plane is assigned as the perfect magnetic conductor (PMC) boundary. Simulation is done with frequency domain solver. Simulation is completed within 2- to 4-GHz frequency range and with the normalized impedance of 50 Ω .

4 Results and discussion with FR-4 substrate material

The transmission (S_{21}) characteristics in dB with respect to frequency in GHz, which were obtained from simulation of the proposed unit cell structure, are shown in Figure 2(A). From the plot of Figure 1, it is clear that the maximum resonance occurs at 3.45 GHz under C-band of microwave spectra. Moreover, the phase spectra corresponding to S_{21} and S_{11} are shown in Figure 2(B).

The distribution of surface current at resonance frequency for the above unit cell is shown in Figure 3(A). As the gap between the SRR rings act as capacitors, they store charge when they are subject to an alternating magnetic field. Therefore, it prevents a flow of current along the

Figure 2: (A) Plot of transmission coefficient (S_{21}) vs. frequency and (B) phase spectra of S_{21} and S_{11} with FR-4 substrate.

Figure 3: (A) Current distribution in the unit cell structure and (B) real value of effective permeability (μ) versus frequency with FR-4 substrate.

copper bar that is contributed from the opposite current following through the SRR rings and constitutes negative transmittance.

To identify the effective parameters of medium, the plot for permittivity, permeability, and refractive index was drawn from the complex S_{11} and S_{21} parameters by the NRW (Nicolson-Ross-Weir)-and DRI (Direct-Refractive-Index) technique described in Ref. [10]. The plot of effective permeability and effective permittivity with respect to frequency is shown in Figures 3(B) and 4(A), respectively. In case of permittivity (ϵ), a negative value ($\epsilon = -20$) corresponding to resonance frequency of 3.45 GHz is shown in Figure 5. On the other hand, for permeability (μ), a positive value ($\mu = 9.84$) is shown in Figure 6 at the same frequency. Therefore, it can be termed as ENG (epsilon negative) metamaterial. Also a near-zero refractive index appears with positive value of $\eta = 0.376$, at near resonance frequency of 3.5 GHz shown in Figure 4(B). It maintains

a bandwidth of 3.26 GHz to 3.60 GHz as the value of S_{21} remains under -10 dB within that range of frequency with a near zero refractive index (NZRI).

5 Analyses with Rogers RT 6010 substrate material

To observe the effect of different substrate material, first, we placed the Rogers RT 6010 dielectric material as a substrate instead of the FR-4 substrate with the same dimension. The value dielectric loss-tangent and constant of that Rogers RT 6010 is 0.002 and 10.2, respectively.

By the substrate material, there are two different resonance points found in the plot of S_{21} after simulation and shown in Figure 5(A). However, in case of FR-4 material, only resonance point is obtained. The values

Figure 4: (A) Real value of effective permittivity (ϵ) versus frequency and (B) real value of refractive index (η) versus frequency with FR-4 substrate.

Figure 5: (A) Magnitude of transmission coefficient (S_{21}) in dB against frequency and (B) real value of effective permittivity versus frequency with Rogers RT 6010 substrate.

Figure 6: (A) Real value of effective permeability versus frequency and (B) real value of refractive index versus frequency with Rogers RT 6010 substrate.

of effective refractive index, permeability, and permittivity are extracted by using the similar procedure that we mentioned in the earlier section and the related plots also drawn.

The permittivity (ϵ) graph exhibits a sharp negative peak about a frequency range of 2.36 GHz to 3.32 GHz, and it was shown in Figure 5(B). The permeability graph also exhibits a negative value at the frequency of 2.36 GHz shown in Figure 6(A). Therefore, in this case, we can declare the material as a DNG metamaterial at the frequency of 2.36 GHz. Moreover, it exhibits positive going slope at 3.32-GHz frequency, so in this point of frequency, it acts as an ENG metamaterial.

The DNG property can be further justified from the refractive index graph shown in Figure 6(B), as it exhibits its negative value for the frequency range of 2.36 GHz to 2.63 GHz, and similar things happen in the case of 3.91-Hz to 4-GHz frequency. Therefore, by changing the substrate material, only the property of metamaterial can be changed.

The dielectric constant of a material depends on internal structure and raw compositions of it. When electromagnetic waves propagated, through a material, its electric and magnetic fields oscillate as sinusoidal pattern. The electrical conductivity of any material that actually depends on the internal structure of the material dominates the velocity of EM wave through it. The relative speed of an electrical signal that travels through the material varies according to the variation of its internal structure, and this variation results different types of transmission characteristics.

6 Analyses with lossy polyimide substrate material

By following a previous strategy, we carried further investigation by replacing earlier substrate material with a

new dielectric consisting of a lossy polyimide substrate that contains dielectric constant of 3.5 and loss-tangent of 0.0027. The dimension of this new substrate material is considered similar as the previous substrates.

By this substrate material after simulation, two different points of resonance are found also in the graph of S_{21} at 2.56 GHz and at 3.7 GHz and are shown in Figure 7(A). However, in the case of FR-4 material, only one resonance point is obtained. The values of effective refractive index, permeability, and permittivity were extracted by using the similar procedure that we mentioned in the earlier section and the related plots were also drawn.

Now, we see that permittivity (ϵ) shows negative peak at the vicinity of the resonance points at 2.56 GHz and at 3.7 GHz, and this is seen in Figure 7(B). Similarly, in case of permeability at the 2.56 GHz, it shows positive value $\mu=3$, and at 3.7 GHz, the permeability is found negative of value, $\mu=-53.5$, and it is seen in Figure 8(A). So, the

material can be characterized as SNG at the frequency of 2.56 GHz. On the other hand, at 3.7 GHz, the material acts as DNG metamaterial for the proposed metamaterial design on polyimide substrate material.

The DNG property can be further justified in this case also from the refractive index graph shown in Figure 8(B), as it exhibits negative value for the frequency range of 3.60 GHz to 3.70 GHz. Therefore, it is a further evidence of our previous statement that, by changing the substrate material, only the property of metamaterial can be changed.

7 Analyses with lossy aluminum nitride substrate material

Again, we replace the FR-4 substrate with a lossy aluminum nitride substrate material that contains dielectric

Figure 7: (A) Magnitude of transmission coefficient (S_{21}) in dB against frequency and (B) real value of effective permittivity versus frequency with lossy polyimide substrate.

Figure 8: (A) Real value of effective permeability versus frequency and (B) real value of refractive index versus frequency with lossy polyimide substrate.

constant of 8.6 and dielectric loss-tangent of 0.003. The dimension of this new substrate material is considered similar as that of the previous substrates (i.e. length and width are equal to 30 mm with 1.6-mm thickness).

In this case, three different resonance points are found in the plot of S_{21} at 2.39 GHz, 3.3 GHz, and 3.55 GHz after simulation, as shown in Figure 9(A). However, in the case of FR-4 material, only resonance point is obtained. The values of effective refractive index, permeability, and permittivity are extracted by using the similar procedure that we mentioned in the earlier section, and the related plots are also drawn.

Now, we see that permittivity (ϵ) shows sharp negative peak at the vicinity of the resonance points at 2.39 GHz, 3.3 GHz, and 3.55 GHz with consecutive real value of $\epsilon = -22.7$, $\epsilon = -10.1$, and $\epsilon = 7.33$, which is seen in Figure 9(B). Similarly, in case of permeability at 2.39

and 3.33 GHz, it shows consecutive positive real value, $\mu = 27.3$ and $\mu = 48.9$, and at 3.55 GHz, the permeability is found negative of value, $\mu = -41.12$, and this is seen in Figure 10(A). So, the material can be characterized as ENG at the frequencies of 2.39 GHz and 3.33 GHz and μ -negative (MNG) at 3.55 GHz according to transmission resonance (S_{21}) points in Figure 9(A). On the other hand, at 3.48 GHz, the material acts as double negative (DNG) metamaterial for the proposed design on aluminum nitride substrate material.

The refractive index curve that is seen in Figure 10(B) shows the DNG characteristics at a frequency of 3.17–3.48 GHz and at a frequency of 3.62–3.89 GHz for metamaterial on aluminum nitride. Therefore, it depicts that the proposed metamaterial within this frequency range can be characterized as DNG metamaterial on aluminum nitride substrate.

Figure 9: (A) Magnitude of transmission coefficient (S_{21}) in dB against frequency and (B) real value of effective permittivity versus frequency with lossy aluminum nitride substrate.

Figure 10: (A) Real value of Effective permeability versus frequency and (B) real value of refractive index versus frequency with lossy aluminum nitride substrate.

8 Comparative analyses for different substrate materials

In Table 1, we see the significant comparisons due to the effect of different substrate materials. It is seen from the table that with increasing value of dielectric constant of different substrates, the resonant frequency range is decreasing. However, the proposed metamaterial structure shows double negative properties if we use Rogers RT-6010 substrate and lossy polyimide substrate material. It is also mentionable that due to the substrate of high dielectric constant, the material shows double negative characteristics at low frequency. On the other hand, the material shows double negative characteristics at some increased frequency point due to the effect of substrate of comparatively low dielectric constant. Another mentionable point is, at a frequency of 3.6 GHz for FR-4 substrate, the material shows NZRI characteristics, whereas at the same frequency for polyimide substrate

material, the material shows double negative characteristics. In this case, the difference between the dielectric constant of FR-4 and polyimide is 0.7. So, it demonstrates that only 20% change in dielectric constant of the substrate has turned the ENG (or single negative) metamaterial to double negative metamaterial. We have found MNG characteristics at a frequency of 3.55 GHz using aluminum nitride as substrate material, which was ENG for FR-4 substrate for the design. In addition, it shows ENG characteristics at 3.33 GHz for both aluminum nitride and Rogers RT-6010 substrate material.

A noteworthy matter is that the proposed metamaterial shows increasing frequency performance with decaying dielectric constants of the substrate, which is seen in Figure 11(A). However, it is clear from these analyses that using the above structure, we can have different types of metamaterial by changing the substrate but all in S-band microwave spectra. Moreover, in Figure 11(B), it is seen that due to the change in dielectric property (from high

Table 1: Comparisons for the effect of popular substrates on the metamaterial structure at significant frequency.

Substrate material	Dielectric constant of the slab	Frequency band (GHz)	Metamaterial type
Rogers RT-6010	10.2	2.36–2.63; 3.33	DNG; ENG
Aluminum nitride	8.6	2.39, 3.33; 3.55	ENG; MNG
FR-4	4.2	3.45; 3.6	ENG; NZRI
Polyimide	3.5	3.6–3.7	DNG

Figure 11: (A) Minimum points of resonance frequency against dielectric constants, (B) metamaterial vs. dielectric constants and (C) metamaterial vs. min^m points of resonance frequency in GHz.

to low), the material shows ENG, MNG, NZRI, and DNG characteristics consecutively at the minimum points of resonance frequency. In Figure 11(C), it also evident that the material displays upward slopping curves for ENG, MNG, NZRI, and DNG characteristics with the increasing resonance frequency at minimum points. Table 1 presents the brief comparison of the effects of substrate on the proposed metamaterial.

9 Conclusion

In this paper, we have shown a novel metamaterial structure on FR-4 substrate that resonates at the frequency of 3.503 GHz, which is in the S-band of microwave spectra, and acts as single or ENG metamaterial at that frequency. For the same design on Rogers RT 6010 substrate and polyimide substrate material, it shows double negative characteristics in the frequencies of 2.36 GHz and 3.7 GHz, respectively. Moreover, the material shows ENG characteristics at 3.55 GHz for aluminum nitride substrate material. Besides data communication like Bluetooth, WiMax communications etc., S-band has good applications in the satellite communications. Recently, metamaterial is being used for designing invisibility cloak where S-band metamaterial

can be used for cloaking satellite in military applications. Therefore, this material can be a promising one for satellite applications and other applications of this range.

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