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Design of a Dual Band SNG Metamaterial Based Antenna for LTE 46/WLAN and Ka-Band Applications

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ABSTRACT The non-existing properties of the metamaterial surfaces can be utilized to improve the antenna radiation characteristics. In this article, a design and performance analysis of a Single Negative (SNG) metamaterial based antenna is imparted for LTE 46/WLAN and Ka-band (like in satellite communication for the receiving side) applications. The unit cell of the metamaterial surface exhibits negative permittivity and positive permeability; yielding a high magnitude positive refractive index, is used to improve and analyze the performance of the proposed monopole antenna element. The proposed SNG based antenna covers a -10 dB bandwidth from 5.35-5.69 GHz (LTE 46/WLAN) and 17.81-20.67 GHz (Ka-band). The total size of the proposed antenna element is 20.2×28.4 mm^2 while a 2×3 SNG metamaterial surface is used at the back of the antenna element which improves the gain from 4.52 dB to 9.13 dB for the desired Ka band and 1.17 to 5.04 dB for the LTE 46/ WLAN band. Furthermore, for the LTE 46/WLAN frequency band, the impedance matching also gets better, resulting in the return loss improvement from -11 dB to -32.4 dB. Moreover, the radiation efficiency is also improved by more than 10 % for the Ka band after employing the SNG metamaterial surface. The measured results fall in good agreement with the simulated one and make the proposed SNG metamaterial based antenna design competent for the LTE 46/WLAN and Ka-band (like in satellite communication for the receiving side) applications.

INDEX TERMS Antenna, high gain, ka-band, metamaterial, SNG, 4G/WLAN.

I. INTRODUCTION

The periodic structures holding a property of negative permittivity and permeability, creating a negative refractive index or a high magnitude positive refractive index have been able to attract the attention of the researcher due to their non-existing properties in the natural materials; named metamaterials [1]–[3]. That's why these materials are considered as an artificial engineered material. There are different types of metamaterials like double negative (DNG), single negative (SNG) and double positive metamaterials [4]. The metamaterials are placed into these categories based on the epsilon and mu of the dielectric. As the SNG metamaterial is that one with the epsilon negative or mu negative, while the metamaterial with the epsilon and mu, both negative is called a DNG and when both are positive, so it is named as double positive (DPS). Each type of the metamaterial has a specific effect on the performance of an antenna in terms of gain,

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efficiency, polarization and many more, when it comes in the close proximity of it as a ground plane, reflector and superstrate etc., [5]–[7].

The monopole antenna has many conventional advantages such as small size, lightweight as well as easy to fabricate. All these features make the monopole antenna, a suitable candidate for the wireless communication systems. But with the flavor of several advantages, there are some problems as well. Like one of major limitations of this antenna is low gain which is not desirable specifically in case of higher frequencies. These requirements have led to much research into antenna development using monopole configuration. To address the gain issues with this type of antenna, the array technique has also been adopted which is quite helpful to tackle the path loss problems at the higher frequencies and besides this multiple input multiple output (MIMO) configuration are also helpful in achievement of higher data rates [8]–[10]. But sometimes the coupling issues are severe in such configuration due to the nearby placement of antenna elements. Apart from that, Fabry-Perot cavity antennas can provide high gain characteristics due to the placement of half wavelength partially reflecting surface (PRS) above an air gap. However, these antennas have some mechanical issues and they face with losses in the thick dielectric PRS as well [11].

Metamaterials are capable to focus the refracted electromagnetic waves in a specific direction due to their non-existing features in the natural materials like DNG, DPS and SNG [12]. Thus, they can be utilized for the monopole antennas to improve the performance in terms of gain, bandwidth, directivity and also for the miniaturization purpose. The development of the antennas based on metamaterials concept is under progress for various communication systems. Although, there are limited studies available for the Ka (17.81-20.67 GHz) and LTE 46/WLAN (5.35-5.69 GHz) bands [13]–[15], collectively based on metamaterials.

Recently, the metamaterials concept has been reported in the literature for different application antennas. As, Reference [16] presents an antenna with a monopole configuration operating at the lower portion of the spectrum i.e., 2.7 GHz. The gain achieved by the authors at the desired frequency band is 3.71 dB which is enhanced by 2.75 dB further after incorporating a metamaterial absorber. Similarly, a dipole antenna with an incorporated metamaterial medium is presented in [17] with an improvement in gain by 2.4 dB at the resonant frequency of 60 GHz. Reference [18] utilized a metamaterial with a negative permeability for an antenna operating at the 5.2 GHz frequency band. The use of SNG metamaterial gives and improvement of 1.5 dB in the gain. Likewise, another type of metamaterials i.e., electromagnetic band gap (EBG) is used for the antenna operating at 3.16-3.36 GHz frequency band [19]. The use of EBG structure make an improvement in gain up to 2.5 dB over the desired frequency band. Similarly, authors present an analysis of different EBG structures on the antenna element in [20] to analyze which type of the EBG surface can give a sufficient improvement in the radiation characteristics. The operating frequency taken for the analysis is 60 GHz, whereas the improvement in gain is observed in 0.65-1.6 dB range by incorporating different metamaterial EBG surfaces. Reference [21] presents a tri-band antenna with an operational frequency bands of 3.3, 14 and 28 GHz. The authors utilize a metamaterial surface for the purpose of gain enhancement at the back of the antenna element. But the reflector purpose is fruitful at the lower frequency band while at the higher frequency bands; the gain improvement varies from 1-2 dB with lot of side and back lobes in the radiation patterns. In [22], an antenna with a matching circuit employed is presented. The matching circuit concept is used to improve the bandwidth, gain and efficiency of the antenna which makes the antenna to cover the bandwidth from 0.25-0.26 GHz. While, a peak gain of 3.54 dB is observed at the desired band with an efficiency of 71% due to the matching circuit.

The gain improvement observed varies within 2-3 dB range in the reported work after employing a metamaterial concept. In this paper, a design and performance analysis of a Single Negative (SNG) metamaterial based antenna is imparted for LTE 46/WLAN and Ka-band (like in satellite communication for the receiving side) applications. A negative permittivity and high magnitude positive refractive index at the Ka-band while near zero refractive index at the lower band i.e., WLAN/ LTE 46 obtained by the SNG metamaterial surface is used to address the monopole configuration issues. Thus, a significant improvement in the performance of the proposed monopole antenna is observed at both the desired two bands specifically in terms of gain with the help of novel SNG metasurface.

A. PAPER ORGANIZATION

The remaining paper layout is as follows. Section II presents the geometry of the reference antenna which is used for the analysis of the metamaterial surface. Along with the geometry of the proposed SNG metasurface is also revealed in this section and its different characteristics are analyzed. The reference antenna incorporating a SNG metasurface is presented in Section III and its detailed performance analysis is depicted, while Section IV concludes the paper.

II. GEOMETRY AND DESIGN PROCEDURE

This section presents a geometry of the reference antenna which is used for the analysis of the metamaterial surface. Along with the geometry of the proposed SNG metasurface is also revealed in this section and its different characteristics are analyzed. A commercial electromagnetic software i.e., Computer Simulation Technology (CST) Microwave Studio is utilized in the designing and simulation of the proposed designs.

A. ANTENNA DESIGN

Fig. 1 shows the geometry of an antenna element designed in the CST software as a reference for the metamaterial surface employment and analysis purpose. The substrate material used is RT/5880 with a thickness of 0.254 mm and the copper cladding utilized for the upper and lower layer of substrate is of standard thickness 0.035 mm. The length and width of the substrate utilized for the proposed antenna is 20.2 × 28.4 mm^2. The dimensions of the proposed antenna design are provided in Table 1. A truncated ground plane is used to achieve the operation at the desired frequency bands with an optimum performance as shown in Fig. 1(b).

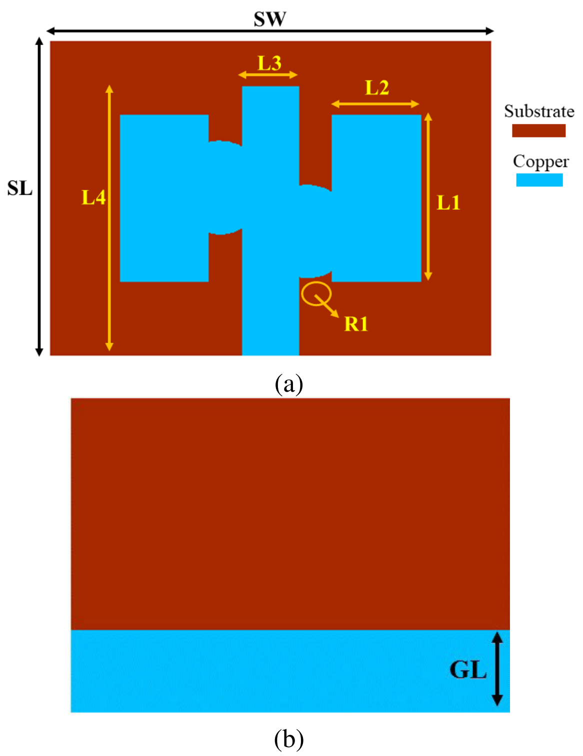

FIGURE 1. **Proposed antenna geometry (a) front view (b) back view.**

TABLE 1. **Proposed antenna dimensions.**

Parameter	Value (mm)	Parameter	Value (mm)
L1	10.8	L3	3.6
L2	5.7	L4	17.4
R1	3.0	SW	28.4
SL	20.2	GL	5.3

In Fig. 2(a), the design evolution stages for the final geometry presented in Fig. 1 are discussed while the response of each stage is demonstrated in Fig. 2(b). As Design-1 radiating portion is a simple rectangular structure and it gives a first resonance at the between 7-8 GHz while the second resonance is observed between 22-23 GHz range. There is another dip between 16-17 GHz frequency range with a magnitude of S11 little bit below 10 dB. To remove the unwanted resonance obtained below 20 GHz; Design-2 is developed by introducing a strip at the top of the radiating element. By introducing a strip, the magnitude of the return loss is increased in case of 20 GHz+ band while a minor disturbance is observed in other dips. Similarly, Design-3 gives more improvement in the return loss magnitude at the 20 GHz+ band as well as a shift in the frequency is observed by introducing a slot in the radiating element. In case of Design-4, the slot is formed towards the opposite side of a slot created in Design-3 to check the effect in terms of return loss. As introducing the slot in Design-4, further shifts the resonance frequency near to 20 GHz. While the resonance near 7 GHz nearly disappear based on 10 dB criteria. But still a resonance gets severe at the 17.2 GHz band which is not desirable. Thus, in Design-5, slots are formed at a time on both sides of the central strip that gives a satisfactory resonance at the 20 GHz band, dedicated for Ka-band applications. While a minor dip is found near 6 GHz; as the changes in the structure are made such that to get a return loss with a low dip in order to study the metasurface effect on the return loss as well. However, the study of the proposed structure shows that it is quite responsible for the resonance at the desired frequency bands.

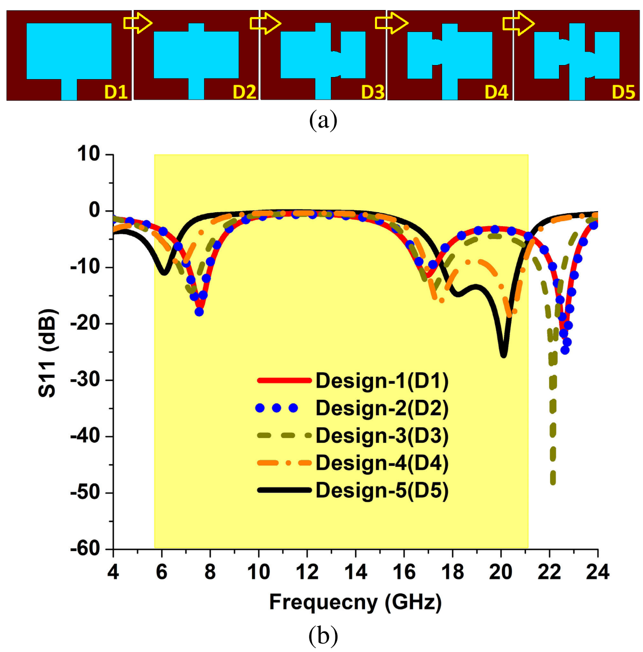

FIGURE 2. **Antenna element: (a) design evolution stages (b) S-parameter comparison.**

In Fig. 3, the analysis for the truncated ground plane is presented by varying a parameter GL. Initially, When the proposed antenna is supported by full ground plane i.e., GL = 20 mm so it is seen that multiple unwanted resonances occur with a return loss magnitude less than -10 dB or quite near to it. Thus, the GL parameter is reduced by 3 to 4 mm gap, step by step and it is observed that few of resonances get stronger in terms of their magnitude. But GL = 9 mm gives a response almost desired and finally, at the 5.3 mm value, the response of the return loss is obtained as targeted.

B. METAMATERIAL SURFACE DESIGN

The geometry of the proposed SNG based metasurface is presented in Fig. 4 with a closed view of the unit element. RT/5880 substrate is used with a thickness of 0.254 mm in the

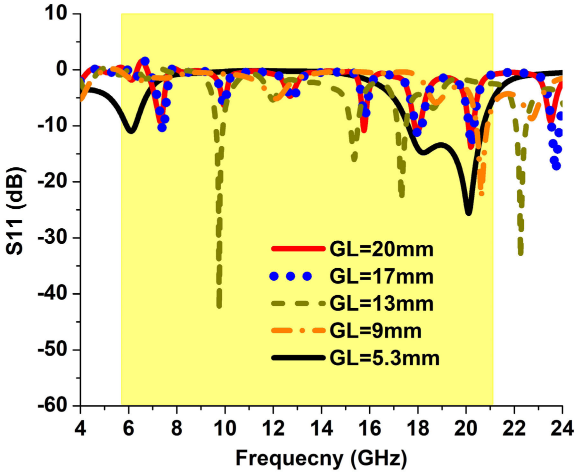

FIGURE 3. Truncated ground analysis.

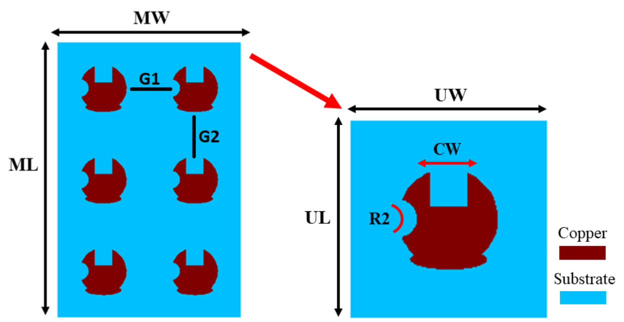

FIGURE 4. SNG metamaterial surface with a closed view of unit element.

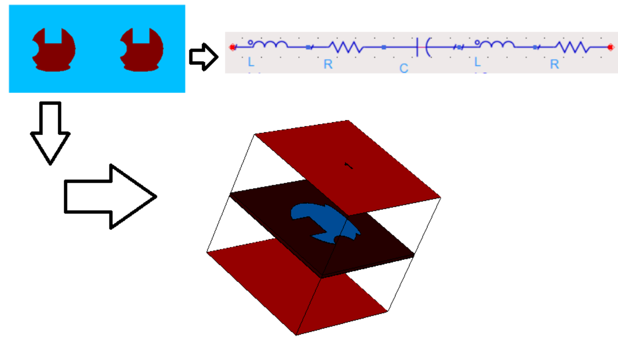

FIGURE 5. Equivalent circuit for the first row of the proposed metasurface with a simulation setup of unit element.

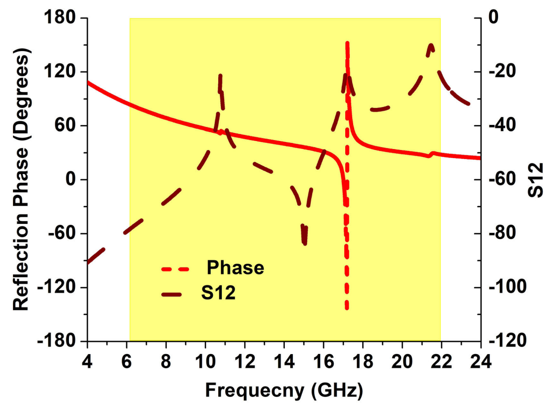

FIGURE 6. Unit element: reflection phase and transmission coefficient.

TABLE 2. Parameters of the unit cell.

Parameter	Value (mm)	Parameter	Value (mm)
ML	30.9	MW	20.6
UL	10.3	UW	10.3
CW	2.0	R2	1.0
G1	5.2	G2	5.2

designing of a unit element and its extended form i.e., 2×3 metamaterial surface. The back side of the substrate is fully copper coated with a standard thickness of 0.035 mm. In Fig. 5, the equivalent circuit model for the first row two unit cells of the proposed metasurface (Fig. 4) is shown. The gap between the two unit cells is represented by the capacitance while per unit cell holds L and R i.e., inductance and resistance combined phenomenon. It means that capacitance can be controlled by varying the gap between the unit cells while changing the unit cell parameters can control the inductance and resistance, jointly. Similarly, the simulated setup is also presented in Fig. 5 for the unit cell. The proposed unit cell is placed between the waveguide ports along the Z-axis in order to resonate the structure. Fig. 6, presents the unit cell reflection phase and transmission coefficient analysis. The proposed structure of the unit cell gives a good stop band for the desired band as well as it is observed that in-phase reflection occurs within the 20 GHz band and near 6 GHz.

The permittivity, permeability and a refractive index response of the element is presented in Fig. 7 which are extracted by using the S-parameter retrieval method [23]. As it can be seen that the proposed metasurface holds asymmetry property while in literature, most of the symmetrical meta-structures have been reported [24]–[28]. That why, it was our keen interest to use an asymmetric metasurface to analyze its effect on the performance of the antenna. Apart from that, the proposed metasurface holds a negative permittivity and positive permeability response which yields a high magnitude positive refractive index of almost 30 dB at the Ka band and at the lower band, a very low refractive index i.e., 0.3 observed which is near to zero as shown in Fig. 7(b). It means that the proposed metasurface acts as a near zero index (NZI) metasurface at the lower band and hence resists the flow of magnetic field in the near field region [29]. While at the higher band, the proposed surface acts as a positive index (PI) metasurface. Thus, the positive index (PI) response effect at the higher band while the NZI response effect at the lower band are interesting to analyze on the performance of the antenna. That's why the geometry of the unit element is adopted such that to get a NZI and PI response at the lower and higher band targeted in the proposed work, respectively.

The surface current distribution is presented in Fig. 8 which shows that the current flow is in the opposite direction within the patch of the unit cell for both the upper and lower frequency bands. This reveals that a good stop band achieved at these frequency bands. Moreover, the current distribution is more focused at the edges of the entire patch of the unit cell

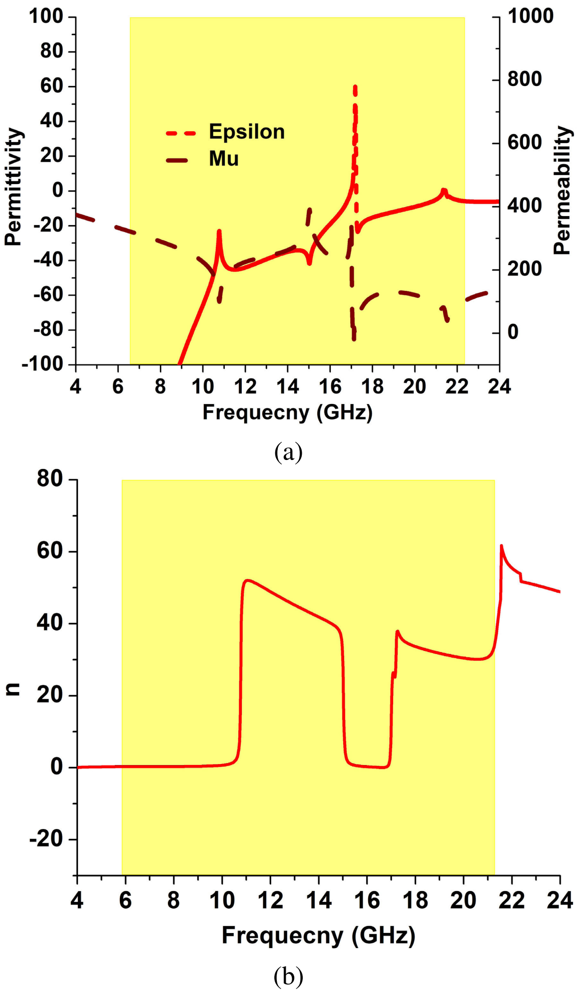

FIGURE 7. Unit cell response (a) epsilon and Mu (b) refractive index.

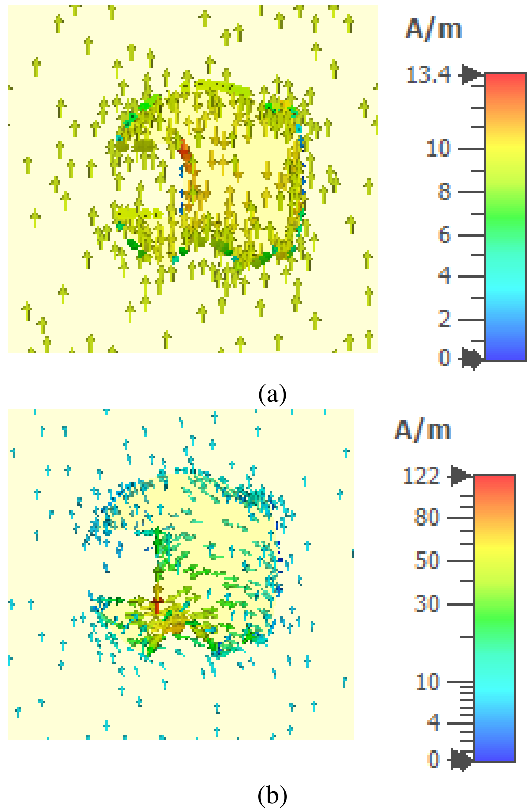

FIGURE 8. Surface current distribution of unit cell at: (a) 5.5 GHz (b) 20 GHz.

for the lower band while the C-shape cut holds intense current in case of the upper frequency band.

III. METAMATERIAL SURFACE BASED ANTENNA

To analyze the effect of the SNG metamaterial surface on the performance of the proposed reference antenna (Fig. 1), the 2 × 3 SNG surface is placed at the back of it as shown in Fig. 9(a). The distance at which the reference antenna is placed at the top of the metasurface matter lot and need be ensured such that interference of the wavs reflected from the SNG surface could interfere constructively with the incident waves to properly put an effect on the performance of the antenna in terms of return loss improvement, gain, efficiency and many more. The equation given below can be utilized to approximate that distance [30] to get a good performance:

$$\varphi - 2\beta H = 2n\pi; \quad n = \ldots - 1, 0, 1 \ldots \tag{1}$$

The equation using few terminologies are: H represents a distance between the antenna and SNG surface while the phase of reflection introduce by it is represented by φ, and β is the free space propagation constant. Thus, the approximated distance at which the significant effect on the performance of a reference antenna can be seen, is 5.45 mm.

The return loss obtained for the reference antenna is compared with the metamaterial based antenna one as shown in Fig. 10(a). As it can be seen that antenna resonate at two frequency bands i.e., Ka band and WLAN/LTE 46 band. In case of the reference antenna the magnitude of the return loss is quite high and below −10 dB for the desired Ka band while the magnitude of the return loss quite low in case of the lower band targeted in the proposed work. But as the SNG based metamaterial surface is employed, the improvement in the return loss level is also observed with a minor shift in the resonant frequency for both the upper and lower bands of interest due to the cavity effect generated by the gap between the antenna and SNG metasurface. It is also worth mentioning that proposed SNG based antenna covers a −10 dB bandwidth from 5.35-5.69 GHz (LTE 46/WLAN) and 17.81-20.67 GHz (Ka-band). As the lower band of the metasurface exhibits the NZI behavior which is helpful to resist the magnetic field flow in the near field region and thus improving the radiation characteristics of the antenna. But at the higher band, the high magnitude positive index (PI) is exhibited by the proposed metasurface. Thus, the effect of both the NZI and PI is interesting to analyze in order to reveal the difference of both on the radiational characteristics of the antenna. For that, in Fig. 10(b), gain comparison has been presented between the reference antenna and SNG metamaterial

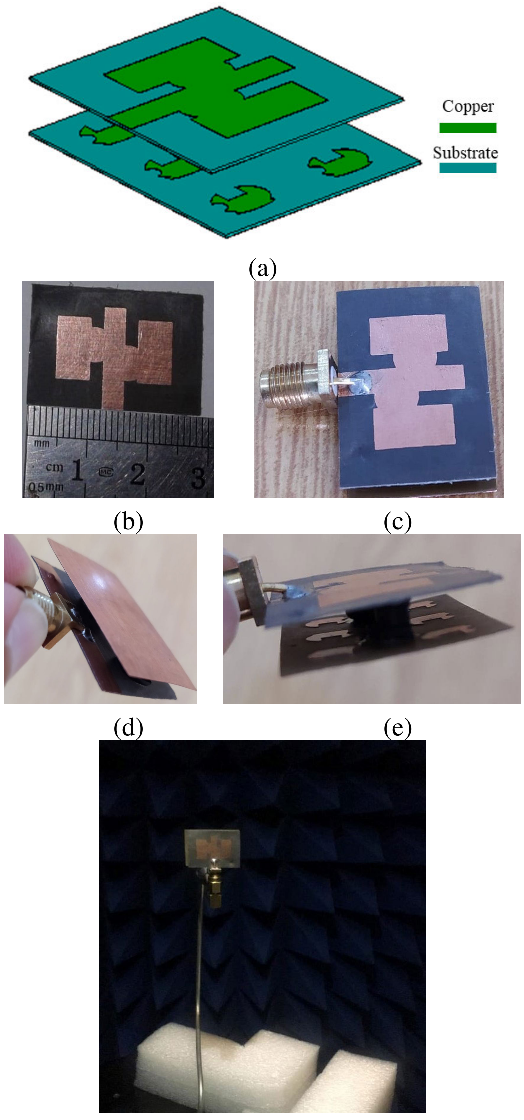

FIGURE 9. Metamaterial based antenna (a) software model (b)-(f) fabricated model snapshots in different scenarios.

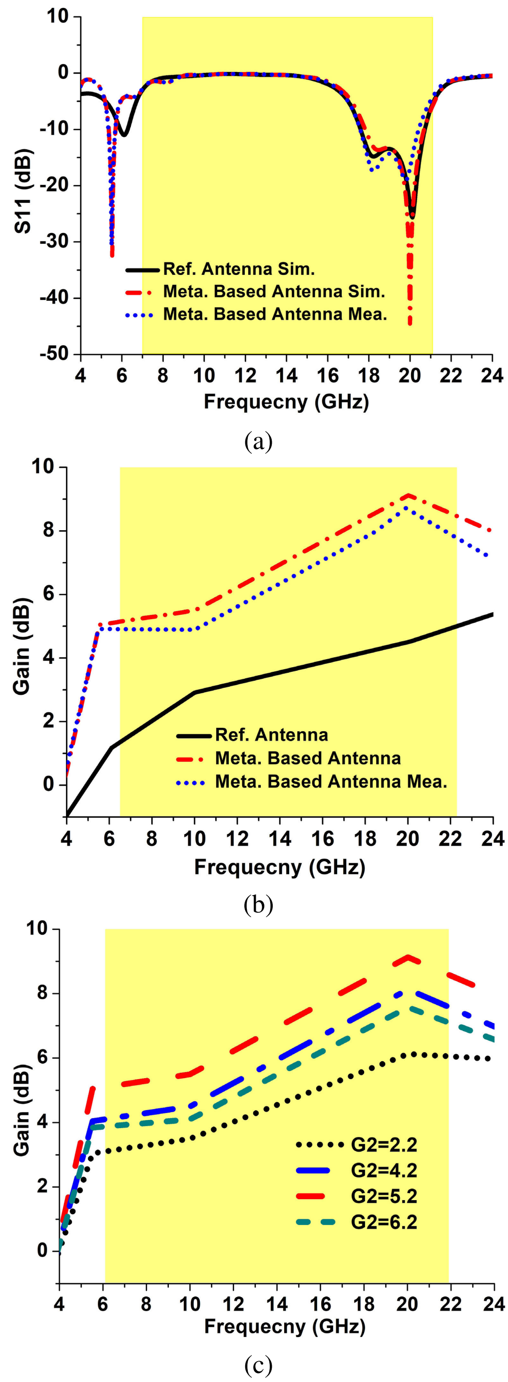

FIGURE 10. Antenna with and without metamaterial surface (a) return loss comparison (b) gain comparison (c) gain variation by varying few parameters.

based antenna. The effect of SNG characteristics is clearly visible on the performance of the reference antenna. As the reference antenna holds a 1.17 dB gain for the lower band and 4.52 dB for the higher band but after employing a metasurface; the rise in the gain obtained is up to 5.04 and 9.13 dB for the lower and upper desired frequency bands, respectively. It is clearly visible that both the NZI and PI behavior of the metasurface improves the gain by 3.35 dB and 4.09 dB at the desired lower and higher frequency band, respectively. Thus, PI metasurface also plays a significant role in achieving a better radiation characteristic, as NZI metasurface plays.

Fig. 10(c) presents the effect on the antenna performance in terms of gain by varying the G2 parameter given in Table 2. By keeping the G1 parameter constant, if G2 value is varied from 2.2 to 6.2 mm; so, it is clearly observed that changing the vertical distance (G2) between the unit cells effect the gain value at the desired frequency bands. This is due to varying the capacitive effect by using G2 parameter. Same effect, as given in Fig. 10 (c) was observed through varying the G1 parameter by keeping G2 one constant. That's why the both the parameters value selected is 5.2 mm where maximum gain improvement is achieved for the operating bands.

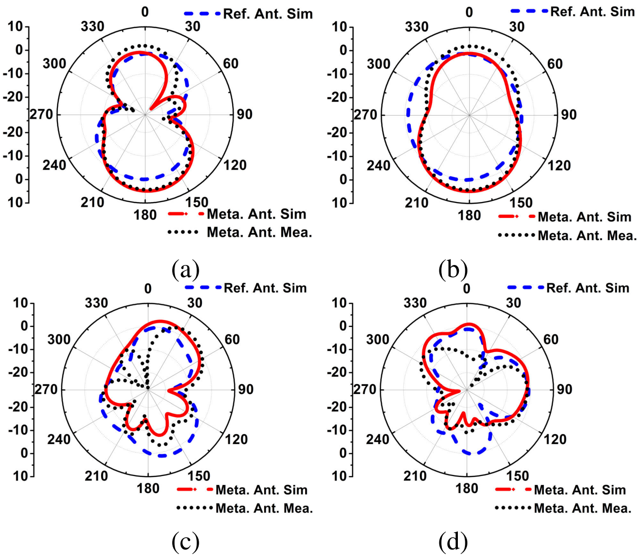

FIGURE 11. Radiation pattern (polar-Co): (a) E-plane for lower band (b) H-plane for lower band (c) E-plane for upper band (d) H-plane for upper band.

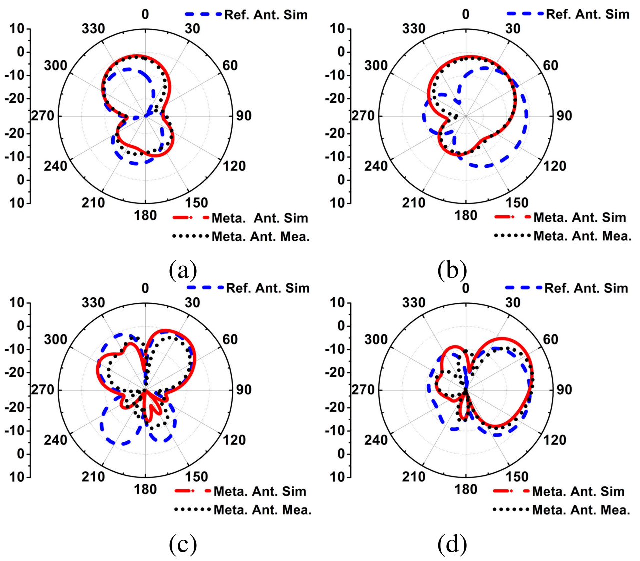

FIGURE 12. Radiation pattern (polar-Cross): (a) E-plane for lower band (b) H-plane for lower band (c) E-plane for upper band (d) H-plane for upper band.

The polar plots of the radiation patterns in terms of co and cross polarization are shown in Fig. 11 and 12, respectively, for both the upper and lower frequency bands targeted in the proposed work in the two different planes i.e., E and H. A good resemblance between the simulated and measured results is observed while minor discrepancies are due to the measurement setup constraints. After employing a metasurface, the omnidirectional radiation patterns are obtained for the lower band due to the refractive index nearness to zero while quite directive patterns are achieved for the higher band because of the high magnitude positive refractive index as shown Fig. 11. Thus, this effect also signifies the importance of PI metasurface that they can play a better role in reduction

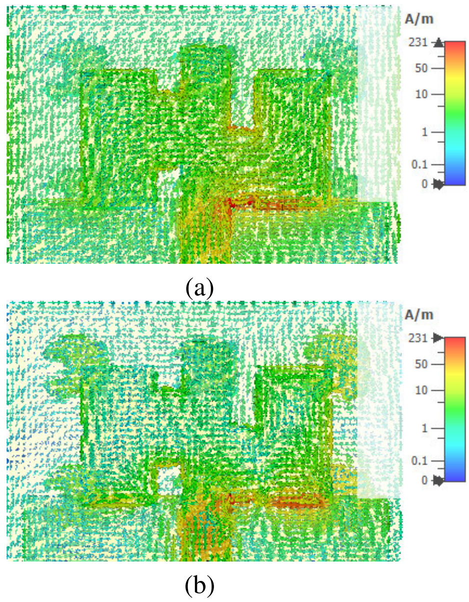

FIGURE 13. Surface current distribution for meta-based antenna: (a) lower band (b) higher band.

of unwanted lobes with the main radiation beam as compare the NZI one. Fig. 13 presents the surface current distribution for the meta-based antenna. For the lower frequency band, the surface current is intense across the entire antenna while for the upper band, the few edges mostly contribute.

In Fig. 14, the radiation efficiency for the proposed antennas is presented and compared. As employing the metasurface gives rise in the efficiency as well. Specifically, in case of higher band, more than 10% increase is observed due to the quite focused radiation patterns at the higher band. As the metasurface holds a high magnitude positive refractive index, in-phase reflection, and high stop band feature, jointly at the higher band; thus, increases the radiation efficiency at the higher band significantly. While at the lower band, the NZI phenomenon occurs due to which a quite low level in-phase reflection occurs; that's why the lower level increase in the efficiency observed at the lower band. However, for the non-operating bands, the high stop band feature of the proposed metasurface resists the radiation characteristics.

In Table 3, the comparison of the proposed work with the reported work is presented. As the development of the antennas based on metamaterials concept is under progress for various communication systems. Although, there are limited studies available in the reported work for the Ka (17.81-20.67 GHz) and LTE 46/WLAN (5.35-5.69 GHz) bands, collectively based on metamaterials and specifically holding a combination of PI and NZI response. Furthermore, the analysis of the Table 3, shows that the compactness was also the issue in the reported literature. As it can be seen that the air gap between the antenna element and metasurface was quite high as compared to the proposed work. Across that our work is dominant due to the quite good gain improvement, very stable bandwidth, affordable air gap between the antenna

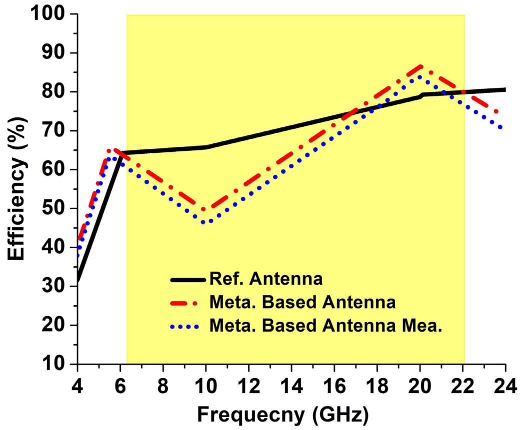

FIGURE 14. Radiation efficiency of the antenna in different cases.

TABLE 3. Comparison of the proposed work with the state of art.

Ref.	Freq. Band (GHz)	Refr. Index/ Meta. type	Gain Im-prov. (dB)	Size (mm^2)	BW. (GHz)	Air Gap b/w Ant. and Meta. (mm)
[16]	2.7	–	2.75	116.5x62.5 (1.05x0.57 λ_o)	<1	10
[17]	60	SNG	2.4	16.25x14 (3.25x2.8 λ_o)	7	–
[18]	5.2	SNG	1.5	6.2x11 (0.108x0.2 λ_o)	0.2	7.5
[19]	3.26	–	2.5	–	0.2	–
[20]	60	–	0.65-1.6	>8x8 (1.61x1.61 λ_o)	13	–
[21]	3.3, 14, 28	–	3.71, 1.88, 0.21	45x40 (0.5x0.45, 2.2x2.0, 4.5x4.0 λ_o)	0.57, 1.68, 3.94	10
[24]	5.6	DPS	4.2	46x36 (0.87x0.68 λ_o)	1.8	3.5
Prop.	5.5, 20	NZI/PI /SNG	3.35, 4.09	20.6x30.9 (0.38x0.56, 1.38x2.05 λ_o)	0.34, 2.86	5.45

element and metasurface with compact size. All these features make the proposed design contribution significant over the existing reported work.

IV. CONCLUSION

In this paper, a unique property of the metamaterials is utilized to analyze the performance of the antenna. The unit cell exhibiting a negative permittivity and positive permeability; yielding a high magnitude positive refractive index, is used to improve and analyze the performance of the proposed antenna element. The proposed SNG based antenna covers a -10 dB bandwidth from 5.35-5.69 GHz (LTE 46/WLAN) and 17.81-20.67 GHz (Ka-band). A 2 × 3 SNG metamaterial surface is used at the back of the antenna element which improves the gain from 4.52 dB to 9.13 dB for the desired Ka band and 1.17 to 5.04 dB for the LTE 46/ WLAN band. Furthermore, for the LTE 46/WLAN frequency band, the impedance matching also gets better, resulting in the return loss improvement from -11 dB to -32.4 dB. Moreover, the radiation efficiency is also improved by more than 10% for the Ka band after employing the SNG metamaterial surface. The measured results fall in good agreement with the simulated one and make the proposed SNG metamaterial based antenna design competent for the LTE 46/WLAN and Ka-band (like in satellite communication for the receiving side) applications.

REFERENCES

[1] B. Khan, B. Kamal, S. Ullah, I. Khan, J. A. Shah, and J. Chen, "Design and experimental analysis of dual-band polarization converting metasurface for microwave applications," *Sci. Rep.*, vol. 10, no. 1, p. 15393, Dec. 2020.

[2] F. Ling, Z. Zhong, R. Huang, and B. Zhang, "A broadband tunable terahertz negative refractive index metamaterial," *Sci. Rep.*, vol. 8, no. 1, p. 9843, Dec. 2018.

[3] X. Gao, Y. Zhang, and S. Li, "High refractive index metamaterial superstrate for microstrip patch antenna performance improvement," *Frontiers Phys.*, vol. 8, Sep. 2020, Art. no. 580185.

[4] N. Dhar, M. A. Rahman, and M. A. Hossain, "Design and exploration of functioning of a D-Z shaped SNG multiband metamaterial for L-, S-, and X-bands applications," *Social Netw. Appl. Sci.*, vol. 2, no. 6, p. 1077, Jun. 2020.

[5] D. A. Sehrai, F. Muhammad, S. H. Kiani, Z. H. Abbas, M. Tufail, and S. Kim, "Gain-enhanced metamaterial based antenna for 5G communication standards," *Comput., Mater. Continua*, vol. 64, no. 3, pp. 1587–1599, 2020.

[6] F. Li, H. Chen, Q. He, Y. Zhou, L. Zhang, X. Weng, H. Lu, J. Xie, and L. Deng, "Design and implementation of metamaterial polarization converter with the reflection and transmission polarization conversion simultaneously," *J. Opt.*, vol. 21, no. 4, Apr. 2019, Art. no. 045102.

[7] J. Khan, D. A. Sehrai, M. A. Khan, H. A. Khan, S. Ahmad, A. Ali, A. Arif, A. A. Memon, and S. Kha, "Design and performance comparison of rotated Y-shaped antenna using different metamaterial surfaces for 5G mobile devices," *Comput., Mater. Continua*, vol. 60, no. 2, pp. 409–420, 2019.

[8] Y.-Y. Jeong and W.-S. Lee, "Wideband printed half bow-tie antenna array based on a quad-mode reconfigurable feeding network for UAV communications," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 238–248, 2021.

[9] J. Khan, D. A. Sehrai, and U. Ali, "Design of dual band 5G antenna array with SAR analysis for future mobile handsets," *J. Electr. Eng. Technol.*, vol. 14, no. 2, pp. 809–816, Mar. 2019.

[10] D. A. Sehrai, M. Abdullah, A. Altaf, S. H. Kiani, F. Muhammad, M. Tufail, M. Irfan, A. Glowacz, and S. Rahman, "A novel high gain wideband MIMO antenna for 5G millimeter wave applications," *Electronics*, vol. 9, no. 6, p. 1031, Jun. 2020.

[11] M. Jeong, N. Hussain, A. Abbas, S. Y. Rhee, S. M. Lee, S. Gil, and N. Kim, "Performance improvement of microstrip patch antenna using a novel double-layer concentric rings metaplate for 5G millimeter wave applications," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 2, Feb. 2021, Art. no. e22509.

[12] N. Hussain, M.-J. Jeong, J. Park, and N. Kim, "A broadband circularly polarized Fabry–Perot resonant antenna using a single-layered PRS for 5G MIMO applications," *IEEE Access*, vol. 7, pp. 42897–42907, 2019.

[13] D. Martinez-de-Rioja, E. Martinez-de-Rioja, Y. Rodriguez-Vaqueiro, J. A. Encinar, and A. Pino, "Multibeam reflectarrays in Ka-band for efficient antenna farms onboard broadband communication satellites," *Sensors*, vol. 21, no. 1, p. 207, Dec. 2020.

[14] S. Ullah, S. Ahmad, B. A. Khan, F. A. Tahir, and J. A. Flint, "An hp-shape hexa-band antenna for multi-standard wireless communication systems," *Wireless Netw.*, vol. 25, no. 3, pp. 1361–1369, 2019.

[15] H. S. Aziz and D. K. Naji, "Printed 5G MIMO antenna arrays in smartphone handset for LTE bands 42/43/46 applications," *Prog. Electromagn. Res. M*, vol. 90, pp. 84–167, Mar. 2020.

[16] H. Jeong, Y. Kim, M. M. Tentzeris, and S. Lim, "Gain-enhanced metamaterial absorber-loaded monopole antenna for reduced radar cross-section and back radiation," *Materials*, vol. 13, no. 5, p. 1247, Mar. 2020.

[17] B. Zarghooni, A. Dadgarpour, and T. A. Denidni, "Millimeter-wave antenna using two-sectioned metamaterial medium," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 960–963, 2016.

[18] Z. Liu, P. Wang, and Z. Zeng, "Enhancement of the gain for microstrip antennas using negative permeability metamaterial on low temperature co-fired ceramic (LTCC) substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 429–432, 2013.

[19] Z.-J. Han, W. Song, and X.-Q. Sheng, "Gain enhancement and RCS reduction for patch antenna by using polarization-dependent EBG surface," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1631–1634, 2017.

[20] S. Ullah, S. Ullah, and S. Khan, "Design and analysis of a 60 GHz millimeter wave antenna," *J. Teknologi*, vol. 78, nos. 4–3, pp. 63–68, Apr. 2016.

[21] J. Khan, D. A. Sehrai, and S. Ahmad, "Design and performance comparison of metamaterial based antenna for 4G/5G mobile devices," *Int. J. Electron. Commun. Eng.*, vol. 12, no. 6, pp. 382–387, 2018.

[22] A. A. Althuwayb, M. Alibakhshikenari, B. S. Virdee, F. Falcone, and E. Limiti, "Overcoming inherent narrow bandwidth and low radiation properties of electrically small antennas by using an active interior-matching circuit," *IEEE Access*, vol. 9, pp. 20622–20628, 2021.

[23] S. Bhattacharyya, S. Ghosh, and K. V. Srivastava, "A wideband cross polarization conversion using metasurface," *Radio Sci.*, vol. 52, no. 11, pp. 1395–1404, Nov. 2017.

[24] N. Hussain, S. I. Naqvi, W. A. Awan, and T. T. Le, "A metasurface-based wideband bidirectional same-sense circularly polarized antenna," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 30, no. 8, Aug. 2020, Art. no. e22262.

[25] N. Hussain, M. Jeong, A. Abbas, T. Kim, and N. Kim, "A metasurface-based low-profile wideband circularly polarized patch antenna for 5G millimeter-wave systems," *IEEE Access*, vol. 8, pp. 22127–22135, 2020.

[26] N. Hussain, M.-J. Jeong, A. Abbas, and N. Kim, "Metasurface-based single-layer wideband circularly polarized MIMO antenna for 5G millimeter-wave systems," *IEEE Access*, vol. 8, pp. 130293–130304, 2020.

[27] J. Park, M. Jeong, N. Hussain, S. Rhee, S. Park, and N. Kim, "A low-profile high-gain filtering antenna for fifth generation systems based on nonuniform metasurface," *Microw. Opt. Technol. Lett.*, vol. 61, no. 11, pp. 2513–2519, 2019.

[28] H. H. Tran, N. Hussain, and T. T. Le, "Single-layer low-profile wideband circularly polarized patch antenna surrounded by periodic metallic plates," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 29, no. 12, Dec. 2019, Art. no. e21969.

[29] A. Iqbal, A. Basir, A. Smida, N. K. Mallat, I. Elfergani, J. Rodriguez, and S. Kim, "Electromagnetic bandgap backed millimeter-wave MIMO antenna for wearable applications," *IEEE Access*, vol. 7, pp. 111135–111144, 2019.

[30] F. A. Tahir, T. Arshad, S. Ullah, and J. A. Flint, "A novel FSS for gain enhancement of printed antennas in UWB frequency spectrum," *Microw. Opt. Technol. Lett.*, vol. 59, no. 10, pp. 2698–2704, Oct. 2017.

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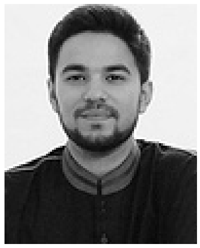

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