Research Article

Design of VHF Horizontal Polarization Omnidirectional Antenna

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Abstract: Horizontally-polarized antennas are usually used in the system of polarization diversity to improve the performance of communication chain and its reliability. Furthermore, the bandwidth of the antenna openly governs the rates of data communication. In order to meet the engineering requirements of high rates for data transmission and multi-band communication, the antenna bandwidth of the communication system needs to be further increased. In this paper we present the scheme of an omnidirectional loop antenna for horizontally-polarized systems. The research status of the horizontally-polarized omnidirectional antenna, and the working principle and radiation characteristics of the small loop antenna are elaborated in detail. The field expression of the loop antenna is deduced from the wave equation, and the characteristics of the far-field and the near-field of the loop antenna are analyzed. On the basis of theoretical analysis, a practical loop antenna is researched and developed for the demands of wireless communication engineering applications. Moreover, we present the related loop antenna technology and how to implement it. The radiation pattern of the antenna is obtained through computer simulations. Our empirical results show that the small loop antenna based on capacitive loading can realize the radiation characteristics of the horizontal polarization omnidirectional pattern. The small loop antenna has the advantages of small size and easy portability, and the small loop antenna operating in the resonant state has a high Q value, which gives it better frequency selectivity. The design and research of this paper have important reference significance for the engineering design and application of the VHF band horizontally-polarized omnidirectional antenna.

Keywords: horizontal polarization; loop antenna; omnidirectional radiation pattern; very-high-frequency (VHF)

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1. Introduction

Antenna plays a very important role in over-the-horizon communication. The following is a brief description of the position and role of antennas in over-the-horizon communication:

Signal transmission and reception: Antennas are key components in wireless communication systems, which are responsible for radiating electromagnetic waves generated by transmitters into space and receiving signals from long distances. In over-the-horizon communication, antennas need to achieve high gain and low sidelobe at low elevation to optimize signal transmission and reception.

Improve the communication distance: over-the-horizon communication usually requires signal transmission over a longer distance, and the performance of the antenna directly affects the distance of the communication. The high performance antenna can reduce the attenuation and distortion of the signal during transmission, thus extending the communication distance.

Anti-interference ability: In over-the-horizon communication, the signal may be affected by various interfering factors, such as multipath effects, atmospheric noise, electromagnetic interference, etc. The antenna design can be optimized for these interference factors, improve the anti-interference ability of the signal, and ensure the stability and reliability of communication.

Multi-function integration: With the continuous development of communication technology, modern antennas not only need to meet the basic signal transmission and reception functions, but also need to integrate a variety of functions, such as beamforming, polarization control and so on. The realization of these functions depends on advanced antenna design.

In short, antenna plays a very important role in over-the-horizon communication. They not only directly affect the performance and stability of the communication system, but also determine the practical application range and effect of over-the-horizon communication.

Meteor trail communication is to carry out meteor burst communication through ionized meteor trail reflection and scattered radio waves. It has the characteristics of anti-interference, not easy to be intercepted, and single-hop communication distance. For a variety of applications where operating at ranges less than 500 km is necessary, meteor scatter is taken into consideration. Over-the-horizon communication can overcome the influence of the curvature of the earth, and the communication distance can reach thousands of kilometres. The communication distance can be increased by increasing the antenna ‘s low elevation angle gain. High gain Yagi antenna or log-periodic antenna arrays at the reception and broadcaster have remained the standard antenna arrangement for meteor burst communication. This arrangement has been proved to perform well at distances more than 700 km, however, it might not be the best at close ranges. Meteor trails are a dispersive medium that can theoretically reflect radio waves from 20 MHz to 110 MHz. However, when the frequency is higher than 60 MHz, the multipath effect becomes obvious and the transmission loss increases rapidly with the frequency, while the low-end frequency threshold is mainly determined by the physical size of the antenna, atmospheric noise, ionospheric attenuation and galactic noise [1]. In practical applications, the frequency band of 35 MHz to 60 MHz is commonly utilized. The center frequency of the antenna in this paper is 45 MHz, and the operating frequency band is 40 MHz~50 MHz.

The characteristics of this system require the omnidirectional horizontally-polarized antenna to have as high gain as possible at low elevation angles, which is conducive to a longer communication distance. Generally, omnidirectional antennas play an important role in wireless communication systems due to their 360º full-angle coverage. In addition, in order to increase the reliability of the communication chain, horizontally-polarized antennas are frequently employed in polarization diversity systems, and the antenna's bandwidth directly affects the data rate of transmission. According to state-of-the-art research, the system with horizontally-polarized antennas at both the transmitter and receiver can obtain an average of 10 dB more power than the system with vertically-polarized antennas at both the transmitter and receiver, which can increase the communication range more effectively [2],[11]. Therefore, it is of great practical significance to study the horizontally-polarized omnidirectional antenna. As a radio wave transceiver, the energy radiated by the antenna usually varies with the location. In the horizontal direction, the energy of the omnidirectional antenna does not change with the direction and presents an mode of uniform distribution.

The energy distribution in the orthogonal direction varies with the position. Generally, the lobe width is opposite to the gain change. Because of its uniform radiation characteristics in the horizontal direction, omnidirectional antennas are generally installed in the center of the required signal coverage. When the time-varying law and form of the electric field vector of the wave transmitted by the omnidirectional antenna satisfy the linear polarization condition, and the direction is parallel to the ground, it is called an omnidirectional horizontally-polarized antenna. The research and design of broadband omnidirectional horizontally-polarized antenna have practical value and profound significance. Therefore, in order to meet the requirements of the high data rates and performance of state-of-the-art multi-band communication systems, the bandwidth of the antenna is expected to be further improved.

The vertical polarization approximates the radiation of an electric dipole, and the horizontal polarization approximates the radiation of a magnetic dipole. Generally, the realization of vertically-polarized omnidirectional antennas is easier, and there are monopole antennas, biconical antennas and other forms [3]. Since magnetic dipoles do not exist, horizontally-polarized omnidirectional antennas need to be realized by arrays. Common types include cylindrical slot arrays [3], cylindrical microstrip arrays [4], [5], turnstile antenna [3], and Alford ring antenna, etc. [3].There are not many horizontally-polarized antennas and most of the omnidirectional antennas are vertically-polarized antennas.

As we know, the traditional implementation structure of the omnidirectional horizontally-polarized antenna is a small loop antenna [12]. However, due to small resistance and large reactance characteristics of the small loop antenna, impedance matching becomes a difficult and tedious activity. Therefore, on the basis of considering impedance matching and omnidirectional radiation characteristics at the same time, in 2006, Lin et al. studied and designed a new type of Alford-type loop antenna (with a bandwidth of 3.4%). The energy of the H surface is uniformly radiated [13]. In 2009, Ahn et al. designed a dual-frequency de-omnidirectional horizontally-polarized antenna (with a bandwidth of about 10%) using a wing-shaped structure, which does not require an external impedance matching circuit and has a simple structure. The disadvantage of these two methods is that the operating frequency range is narrow [14]. In 2014, Chin et al. combined the concept of the turnstile electric field with traditional slot dipoles. The authors used coplanar waveguides for feeding to achieve an omnidirectional horizontally-polarized radiation pattern with a gain of 2.5 dB - 3.4 dB and an operating bandwidth of 15.4% (2.4 GHz - 2.8 GHz). The tested radiation efficiency in the bandwidth is greater than 73% [15]. In 2014, Wang et al. designed a high-gain broadband omnidirectional horizontally-polarized antenna. The antenna array consists of four elements and a circular four-way power divider. Each element contains four pairs of sector dipoles and a broadband bar [16]. The measured data shows that it has obtained 39.4% of the working bandwidth (1.62 GHz - 2.43 GHz), the peak gain within the working bandwidth is 6.4 dB - 7.2 dB, and the radiation efficiency is 88%, but its profile is as high as 390 mm. In addition, some new technologies have been adopted. For example, in 2015, the omnidirectional horizontally-polarized antenna designed by Zhang et al. contains four pairs of dipoles [17]. The band parallel line achieves the purpose of balanced conversion from the coaxial feeder to the antenna, while adding a reflector. The operating bandwidth of the antenna is 39.6% (1.82 GHz - 2.72 GHz). In 2016, Zhou et al. designed and discussed three types of antenna arrays, including 3, 4, and 5 array element dipoles, respectively [18]. The feed network structure is simple and easy to match to the dipole elements. At the same time, the crossover structure is adopted to reduce the crossover. The three antenna arrays work at 1.7–2.7 GHz, covering the DCS 1800, WiFi 2700, and 4G-LTE frequency bands, and the reflection coefficient within the bandwidth is lower than -15 dB. Zhang et al. designed a new structure for the antenna design. The proposed structure consists of four array element dipoles, one arm of the dipole adopts a coupling structure, the feed structure is added with square perturbation, and the operating bandwidth is 51% (1.6 GHz - 2.72 GHz) [19]. In order to further widen the bandwidth, Xiuzhang Cai et al. used planar folded dipoles to form a square antenna array, and designed a broadband feed network with a balun [20]. The structure of the folded dipole enables broadband to be achieved in a small size. In operation, the measured impedance bandwidth reaches 53.2% (1.19GHz~2GHz), the azimuth pattern out-of-roundness is less than 2 dB at 1.2 GHz ~ 1.9 GHz, and increases to 2.8 dB at 2 GHz, with stable peaks in the bandwidth The gain is about 1.2 dB and the polarization purity is greater than 20 dB, however the disadvantage is that the profile is as high as 26.7 mm. ZeDong Wang et al. designed an antenna array by means of mutual coupling [21]. The array element is a sector-shaped printed dipole, and also includes a broadband feed network, sector-shaped parasitic, and a guiding element. Due to the strong coupling effect and impedance matching layer, the steering element is used to increase the gain of the horizontal plane, and the results show that it achieves a 70.2% (1.7 GHz~3.54 GHz) impedance bandwidth and good isotropic radiation characteristics, where the pattern in the 1.7 GHz~3.2 GHz range is not circular. The disadvantage is that the size is 0.85 λL × 0.85 λL × 0.01 λL (λL is the wavelength corresponding to the lowest operating frequency) [6], [7], [8], [9],[10].

A loop antenna is an important type of antenna, which is widely used in wireless communication systems. There are two types of loop antennas: electric large loops and electric small loops. The conductor length and ring size of the electrically large ring are comparable to the wavelength, and the conductor length and the largest linear dimension of the ring perimeter of the electrically small ring antenna are very small compared to the wavelength. The small electric loop antenna with a small ring perimeter can be regarded as a magnetic dipole [25], and the radiation pattern is the same as that of an ideal magnetic dipole, that is, the radiation pattern of the main plane of the ring antenna is omnidirectional, and the zero point appears on the axis perpendicular to the ring plane [24]. The fundamental limitation of electrically small loop antennas determines the restrictive relationship between antenna size and bandwidth, and the development of wireless communication technology requires the realization of broadband miniaturization of antennas [26]. Therefore, how to reduce the size of the antenna while ensuring the broadband characteristics of the antenna and improve the radiation of the antenna efficiency has become the focus of research on horizontally-polarized omnidirectional electrically small loop antennas at this stage [22].At the same time, simplifying the structure of the antenna as much as possible is also a direction that needs to be solved in the future [23].

The major contributions of this article are as follows: (i) the design of a novel horizontally-polarized omnidirectional loop antenna is proposed; (ii) the horizontally-polarized omnidirectional antenna and its working principle and radiation characteristics of the small loop antenna are elaborated; (iii) the field expression of the loop antenna is deduced from the wave equation, and the characteristics of the far-field and the near-field of the loop antenna are analyzed; (iv) a practical small loop antenna is studied on the basis of theoretical analysis for the engineering requirements of wireless communication applications.

This paper is organized as follows. The research status of horizontally-polarized omnidirectional antennas are presented in Section I. The detailed antenna design and its operational theory are discussed in detail in Section II. The model of antenna is analyzed and the antenna radiation characteristic is discussed in detail, and simulation results are presented in Section II. The simulation results show that the proposed design is practical for the miniaturized horizontally-polarized omnidirectional antenna. The conclusion of this paper is given in Section III.

2. Design of Horizontally-polarized Loop Antenna with Omnidirectional Patterns

2.1. Loop antenna basic theory

The infinitesimal loop current can be equivalent to an ideal magnetic current source. Similarly, for a loop antenna with a small circumference used in practice, assuming that the wire is very thin, a small loop antenna is placed on the XOY plane, as shown in Figure 1. The current along the loop antenna can be seen as uniformly distributed, that is given by Equation 1:

$$I_\phi = I_o \qquad (1)$$

where I_o is a constant.

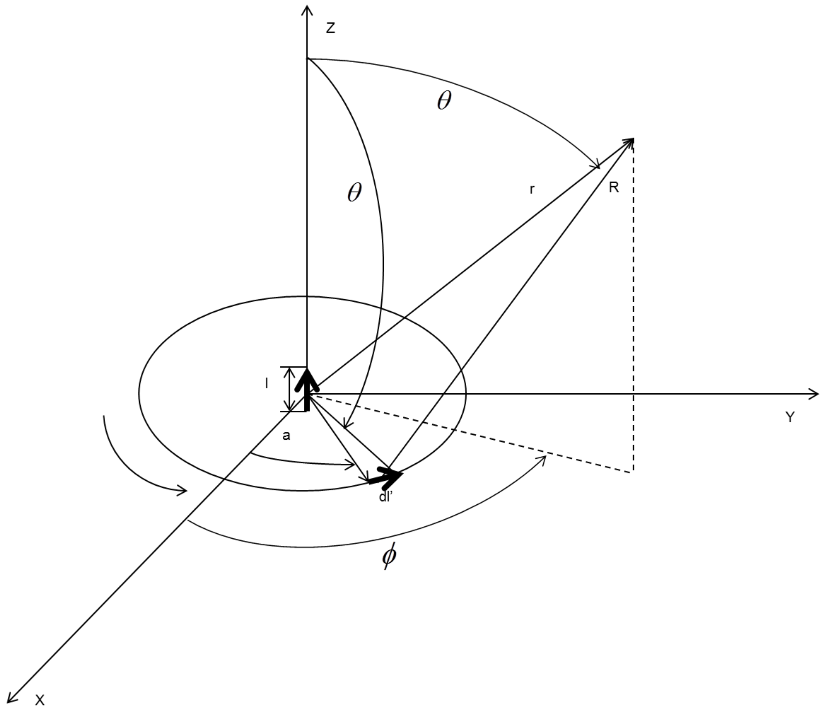

Figure 1. Loop antenna schematic diagram.

From the solution of the current source vector wave equation in electromagnetic field theory:

$$\vec{A}(\mathrm{x,y,z}) = \frac{\mu}{4\pi}\int_C \vec{I}_e(\mathrm{x}',\mathrm{y}',\mathrm{z}')\frac{e^{-jkR}}{R}dl' \qquad (2)$$

Integrating in spherical coordinates:

$$\vec{A}(\mathrm{r},\theta,\phi) = \vec{a}_\phi j\frac{k\mu a^2 I_0 \sin\theta}{4}[1+\frac{1}{jkr}]\mathrm{e}^{jkr} \qquad (3)$$

where R is the distance from a point on the loop antenna to the observation point, r is the radial coordinate of the observation point, k=2pi/λ, dl' is an infinitesimal segment of the antenna, and a is the radius of the loop antenna, θ is the elevation angle,Φ is the azimuth angle. According to the relationship:

$$\vec{H} = \nabla \times \vec{A} \quad (4)$$

$$\vec{E} = \frac{1}{j\omega\varepsilon}(\nabla \times \vec{H} - \vec{J}) \quad (5)$$

Substitute $\vec{A}$ into Equation (4) to obtain $\vec{H}$, and then obtain $\vec{E}$ from Equation (5), the zero components of the electric field and the magnetic field are respectively as follows [7]:

$$\vec{E}_r = \vec{E}_\theta = \vec{H}_\phi = 0 \quad (6)$$

$$\vec{H}_r = j\frac{ka^2 I_0 \cos\theta}{2r^2}[1+\frac{1}{jkr}]\mathrm{e}^{-jkr} \quad (7)$$

$$\vec{H}_\theta = -\frac{(ka)^2 I_0 \sin\theta}{4r}[1+\frac{1}{jkr}-\frac{1}{(kr)^2}]\mathrm{e}^{-jkr} \quad (8)$$

$$\vec{E}_\phi = \eta\frac{(ka)^2 I_0 \sin\theta}{4r}[1+\frac{1}{jkr}]\mathrm{e}^{-jkr} \quad (9)$$

Therefore, the radiation field area of the antenna can be divided into two areas: (i) the far-field area; and (ii) the near-field area according to the value of kr:

1. Far-field （kr >>1）

$$\vec{H}_\theta \approx -\frac{(ka)^2 I_0 e^{-jkr}}{4r}\sin\theta = -\frac{\pi S I_0 e^{-jkr}}{\lambda^2 r}\sin\theta \quad (10)$$

$$\vec{E}_\phi \approx \eta\frac{(ka)^2 I_0 e^{-jkr}}{4r}\sin\theta = \eta\frac{\pi S I_0 e^{-jkr}}{\lambda^2 r}\sin\theta \quad (11)$$

$$\vec{H}_r = \vec{H}_\phi = \vec{E}_r = \vec{E}_\theta = 0 \quad (12)$$

where $S = \pi a^2$ is the geometric area of the loop antenna. It can be seen from the above three equations that the magnetic field only has a component in the θ direction, and the radiation field is zero on the axis of the loop antenna (θ =0°), and the pattern shows a shape as shown in Figure 8.

2. Near-field （kr <<1）

$$\vec{H}_r \approx \frac{a^2 I_0 e^{-jkr}}{2r^3}\cos\theta \quad (13)$$

$$\vec{H}_\theta \approx \frac{a^2 I_0 e^{-jkr}}{4r^3}\sin\theta \quad (14)$$

$$\vec{H}_r = \vec{E}_r = \vec{E}_\theta = 0 \quad (15)$$

In the near-field region (kr << 1), the two components of the magnetic field are in phase in time, while for the electric field, their time phase is 90° out of phase. Therefore, the average power (the real power) is zero, and the energy is in the electric and magnetic fields as well as the field exchange with the source without radiation. Thus, the near-field region is also called the induction field region. The small loop antenna working in the near-field area is also called an induction coil, which transmits signals by inducing an alternating current on the coil through the magnetic field in the near-field area [27].

2.2 Loop antenna model

The FEKO is an electromagnetic simulation software based on the integral algorithm. It has unique advantages in the analysis of electrically small antennas. It is not only convenient to build antenna models but also has fast simulation speed and accurate results. This paper also uses the FEKO application software to establish the antenna model shown in Figure 2.

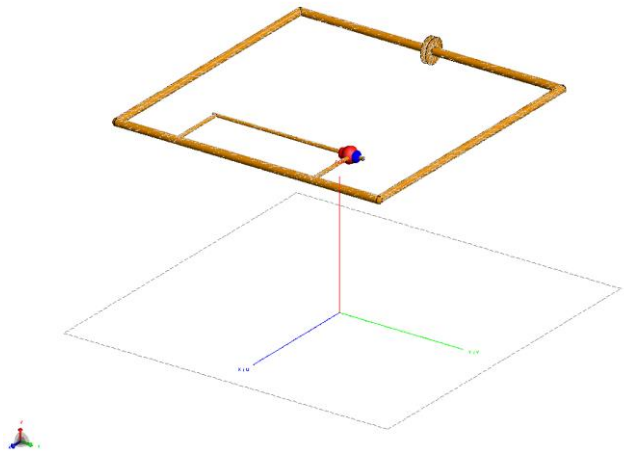

Figure 2. Loop antenna model.

The meshing of the antenna model is shown in Figure 3.

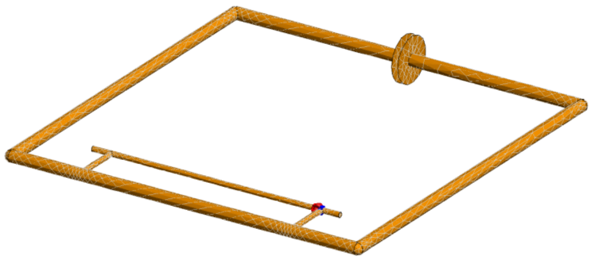

Figure 3. Loop antenna meshing.

After simulation optimization, the side length of the small loop antenna is 0.7 meters, the diameter of the loop is 18 mm, and the antenna conductor material is a copper tube with a diameter of 18mm. The transmitting power of the antenna is 2 kilowatts.

A capacitor is loaded on the loop antenna, and the distance between the two parallel plates of the capacitor can be adjusted. The spacing between the two capacitor plates can be manually adjusted. The longer the distance, the higher the antenna resonance frequency [28].

When the resonant frequency is adjusted to the specified operating frequency, if the voltage standing wave ratio (VSWR) is high, such as greater than 2, the position where the metal rod at the bottom of the loop is connected can be adjusted. By sliding the position of the metal rod, the voltage standing wave ratio (VSWR) can be adjusted, however, generally speaking, the resonant frequency will not be changed.

2.3 Free Space Antenna Radiation characteristic

A reactive element is loaded on the loop antenna to cancel the reactive part, thus increasing the radiation resistance and thereby the radiation efficiency of the antenna can be greatly improved. When the circumference of the loop antenna exceeds 0.1λ, the current cannot be considered to be uniformly distributed along the loop antenna, and the non-uniform current distribution has a great influence on the antenna performance [30].

Therefore, the current on the loop antenna is generally expanded into a Fourier series for analysis:

$$I(\phi) = I_0 + 2\sum_{n}^{m} I_n \cos n\phi \quad (16)$$

The small loop antennas are generally inductive, which is very important for loop antenna design. In the design of the small loop antenna, the loop antenna is equivalent to an inductance, and a resonant circuit is formed by loading reactance elements such as capacitors to make the loop antenna resonate.

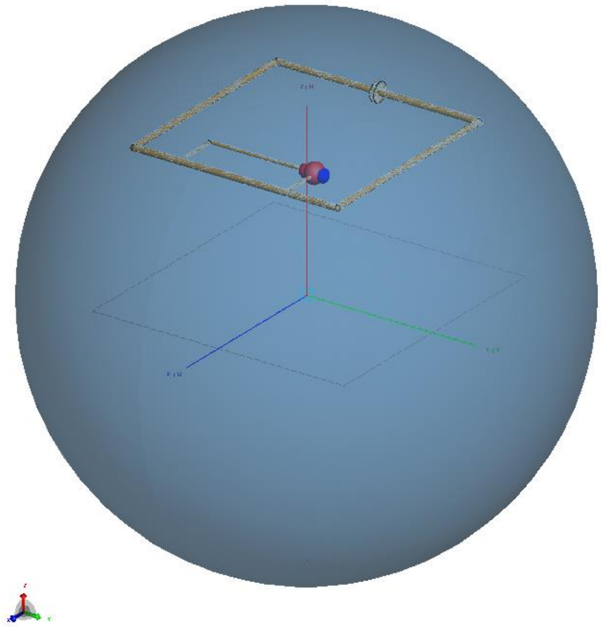

Figure 4. Loop antenna far-field radiation.

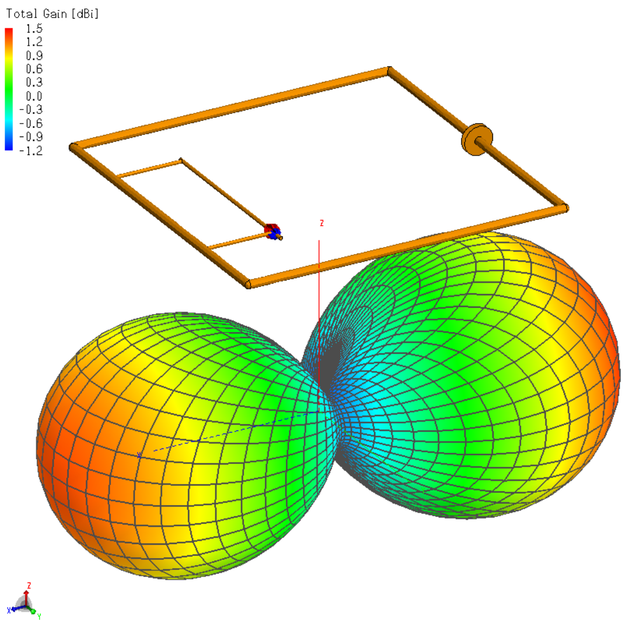

Figure 5. The gain(IEEE) of the proposed loop antenna (3D radiation pattern).

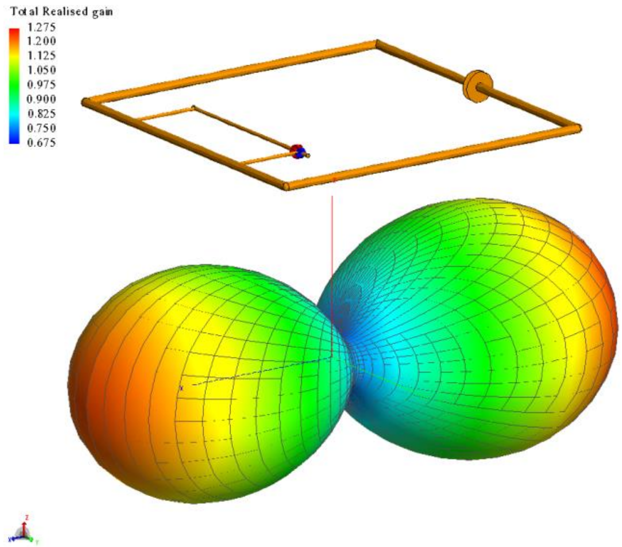

Figure 6. The realized gain of the proposed loop antenna (3D radiation pattern).

The antenna is a horizontally polarized omnidirectional antenna with radiation pattern characteristics similar to that of a monopole antenna. The technical performance specifications of gain greater than 0dB and return loss S11 less than -10dB are achieved in the operating frequency of 40MHz-50MHz.

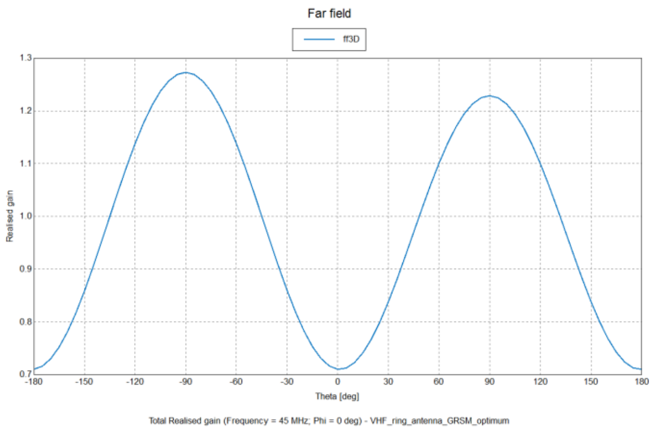

Figure 7. The realized Gain of loop antenna (phi=0 degree plane).

It can be seen that the loop antenna can achieve a horizontally-polarized omnidirectional pattern in the far-field (modeling shown as in Figure 4), like a magnetic dipole antenna, as shown in Figure 5, Figure 6 and Figure 7. Figure 5 is the total gain of loop antenna. Figure 6 is the realized gain of loop antenna. Figure 7 is loop antenna radiation pattern [29]. Figure 8 is the VSWR of the loop antenna. It can be seen from the simulation results that the small loop antenna has a good voltage standing wave ratio and excellent radiation characteristics.

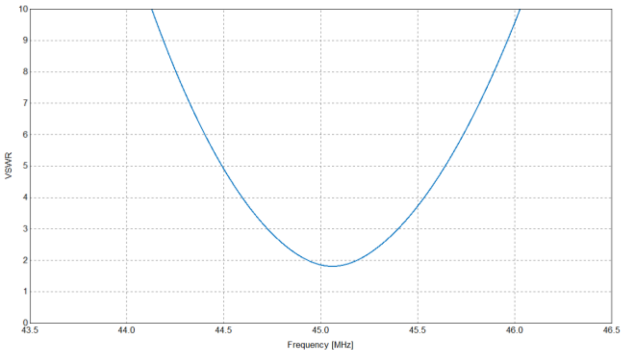

Figure 8. The VSWR of loop antenna.

2.4 Antenna radiation characteristic in the installed state

The carrier platform has a certain degree of influence on the radiation characteristics of loop antenna. Loop Antenna mounted on the carrier platform is shown as Figure 9. The distortion of the loop antenna pattern is particularly obvious. The loop antenna is placed at a position of 1 meter on the carrier platform so as to mitigate the adverse effect of the carrier platform. The specification of antenna gain roundness is deteriorated by the effect of the carrier platform.

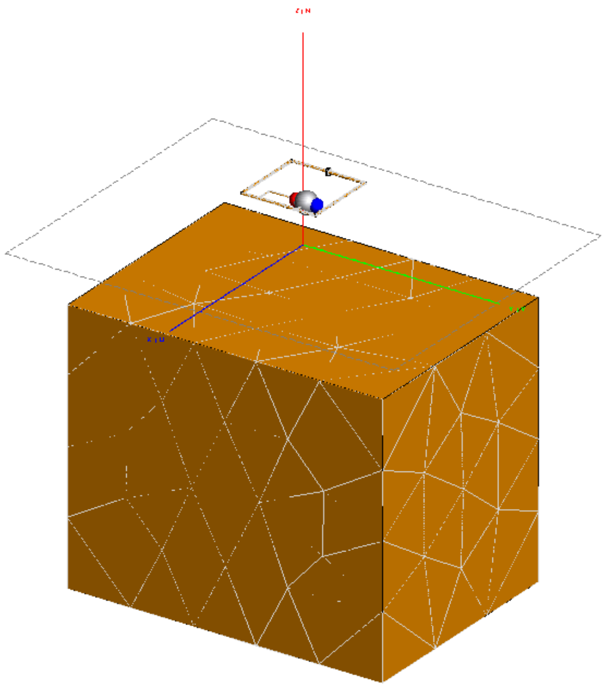

Figure 9. Loop antenna mounted on the carrier platform.

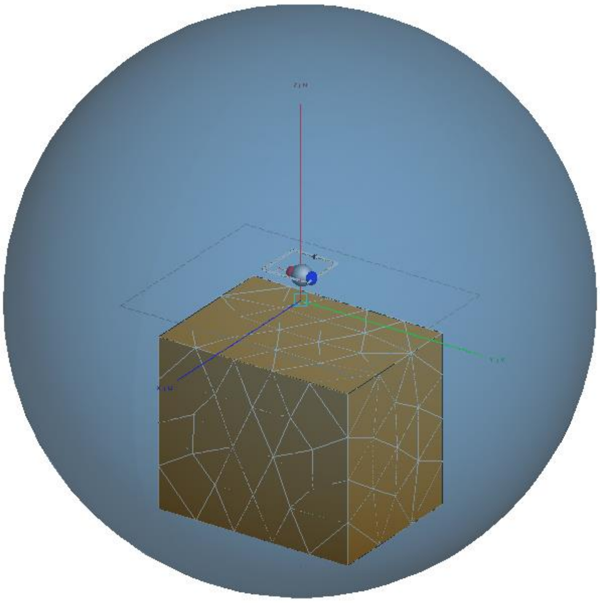

Figure 10. Loop antenna computing.

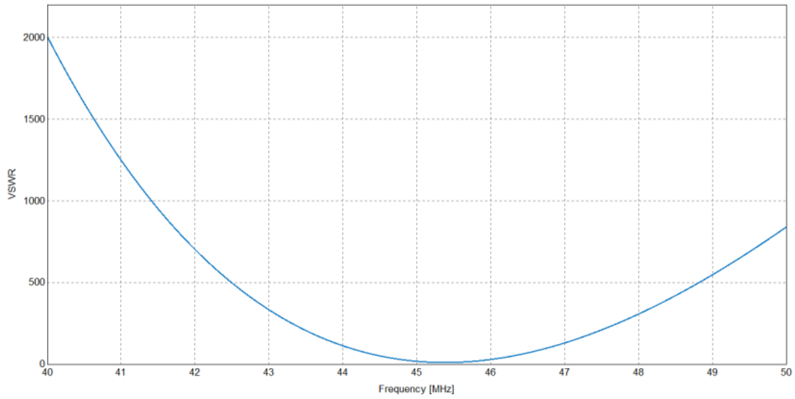

Figure 11. The VSWR of the loop antenna without matching network.

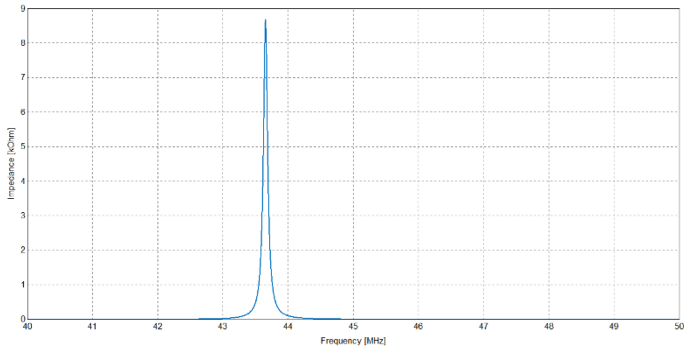

Figure 12. The real part of the loop antenna impedance.

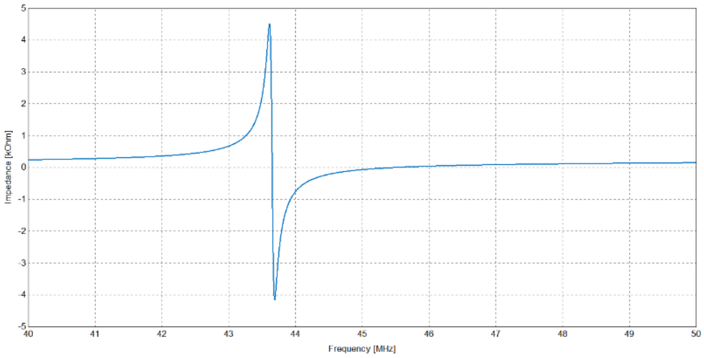

Figure 13. The imaginary part of the loop antenna impedance.

The carrier platform has great influence on the VSWR of the loop antenna. The VSWR of the loop antenna without matching network is shown as Figure 11. The real part of the loop antenna impedance is shown as Figure 12. Imaginary part of the loop antenna impedance is shown as Figure 13.

Figure 14 shows antenna impedance matching range result at frequency 45 MHz. The specific content of the SPICE model file is as follows in Figure 14.

```
Loop Antenna Matching circuit

.SUBCKT GeneralNetwork1 n1 n2
C1 n1 0 103.59p
L1 n1 n2 152.382n
.ENDS GeneralNetwork1

.ENDS
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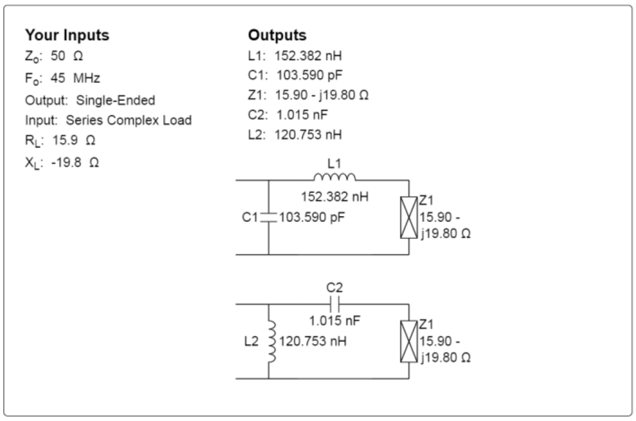

Figure 14. Loop antenna matching network.

By loading the impedance matching network, the impedance of the antenna is matched to the characteristic impedance of the system, 50 ohms. When the center frequency is 45 MHz, L1=152.382 nH, C1=103.59 pF. The modeling of loading the impedance matching network in FEKO is shown in the Figure 15.

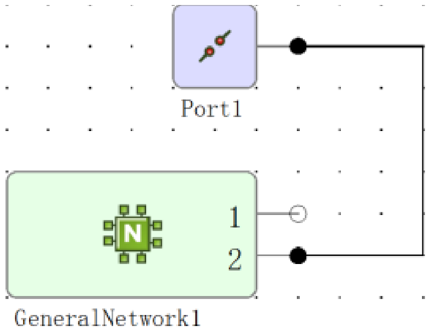

Figure 15. Model of loading matching network in FEKO.

The VSWR after loading the impedance matching network is shown in the Figure 16.

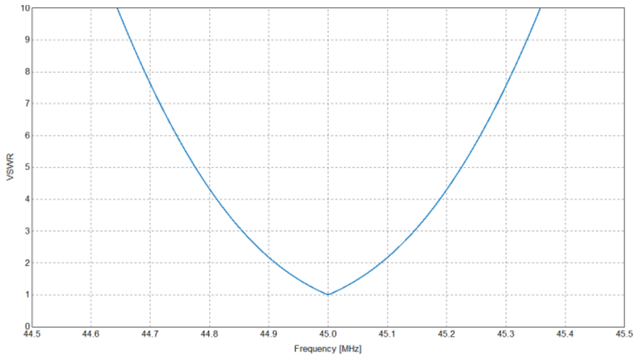

Figure 16. The VSWR of the loop antenna.

The simulated radiation patterns at 45 MHz are depicted in Figure 17.

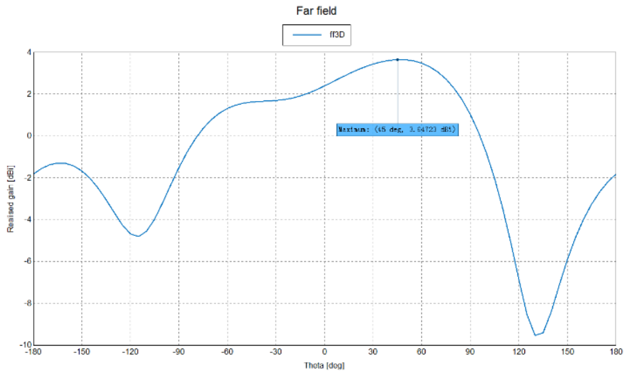

Figure 17. Loop antenna gain mounted on the carrier.

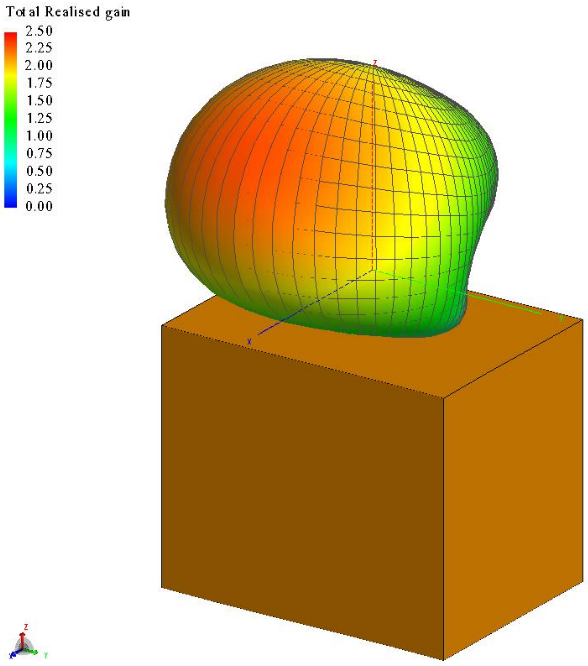

Figure 18. Loop antenna realized gain mounted on the carrier.

The simulated 3D radiation patterns of the loop antenna mounted on the carrier at 45 MHz are depicted in Figure 18.

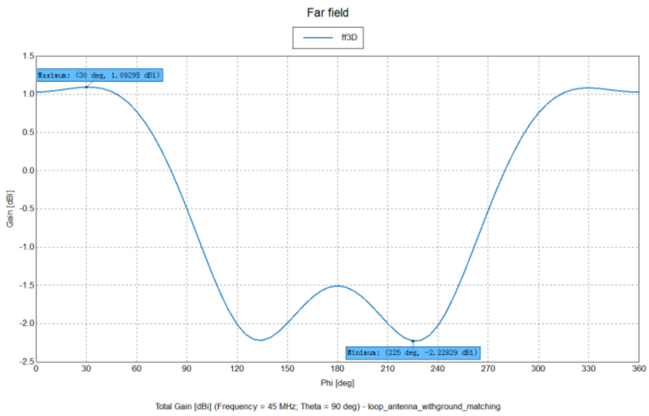

Figure 19. Gain roundness in horizontal cut plane of 0 degree elevation angle.

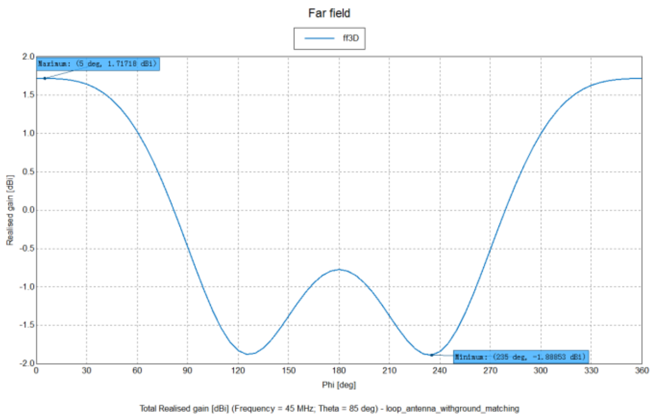

Figure 20. Gain roundness in horizontal cut plane of 5 degree elevation angle.

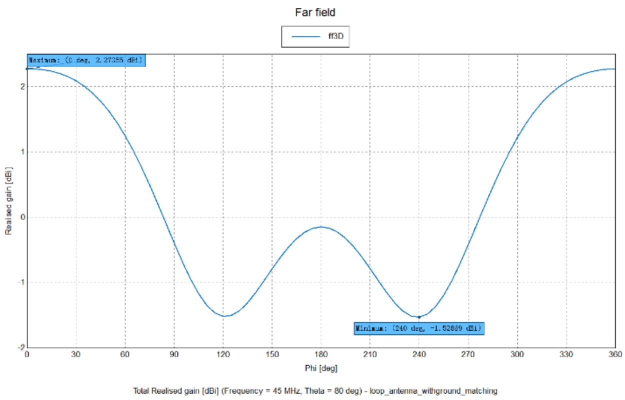

Figure 21. Gain roundness in horizontal cut plane of 10 degree elevation angle.

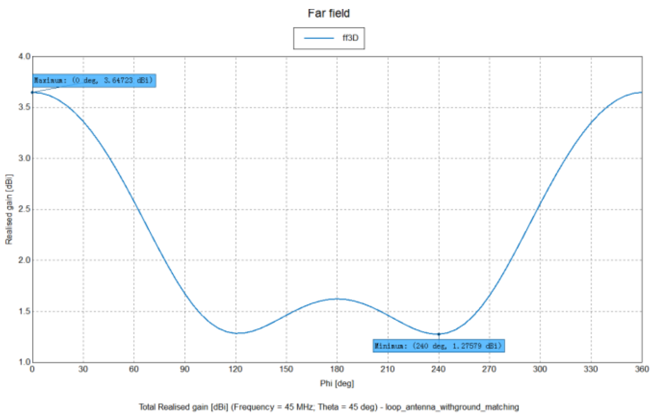

Figure 22. Gain roundness in horizontal cut plane of 45 degree elevation angle.

As observed in Figure 19 ~ Figure 22, gain roundness in horizontal cut plane at each elevation angle is less than 4.5 dB. Moreover, the loop antenna is significantly small, achieves omnidirectional patterns, and matches impedance at VHF band. Over the frequency spectrum, the omnidirectional radiation patterns with small gain fluctuations are possible. The loop antenna shows good omnidirectional characteristics in the operating frequency band.

Figure 23. The photo of loop antenna.

3. Conclusions and Future Work

This paper presents a loop antenna with horizontal polarization omnidirectional pattern in azimuthal plane. The loop antenna is easy to fabricate and has low profile, compact size, and low cost. The design method of capacitive loading and the impedance matching network is also used in the loop antenna design. Simulation results prove that the projected antenna covers the frequency band from 40 MHz to 50 MHz while the reflection coefficient were observed less than -15 dB. In horizontal plane, the design of the loop antenna shows good omnidirectional characteristics. Moreover, in horizontal plane the gain variations are less than 4.5 dB over the whole frequency band. The horizontal polarization omnidirectional radiation patterns are obtained for VHF band applications, which are suitable for Meteor Burst Communication in aircraft or vehicles.

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References

1. Bingxing Hu. 2003. Talking about Meteor trail Communication [J].*Tele-communications Science*.
2. Ding Chao. 2014. Research on Omnidirectional Horizontally-polarized Antenna [D]. Master's Thesis of Xiamen University.
3. John. D. Kraus, Ronald J. Marhefka, 2004.*Antennas* (third Edition), Publishing House of Electronics Industry.
4. Immanual Jayakumar Ramesh, Garg Sarap B K, 1986. A conformal cylindrical microstrip array for producing omnidirectional radiation pattern [J]. *IEEE Transactions on Antenna and Propagation*, Volume 34.10, pp.1258~1261.
5. Hisao Iwasaki, 1996. A microstrip array antenna with omnidirectional pattern fed by CPW, [J], *IEEE Antennas and Propagation society International Symposium*, pp.1912~1915.
6. Huihui Liu, 2010.Research on Ultrashort Wave Horizontally-polarized Omnidirectional Antenna [D]. Master thesis of XIDIAN University.
7. Rudge A W, Milne K, Olver A D, et al. 1983. *Handbook of Antenna Design* [J]. Peter Peregrinus Ltd..
8. Chen, Zhi Ning, Duixian Liu, Hisamatsu Nakano, Xianming Qing, and Thomas Zwick. 2016. *Handbook of antenna technologies*. Springer Publishing Company, Incorporated.
9. Zhang, Zhi-Ya, et al. 2018. A broadband horizontally-polarized omnidirectional antenna for VHF application. *IEEE Transactions on Antennas and Propagation,* Volume 66.5, pp. 2229-2235.
10. Lesanu, Cezar-Eduard,Adrian Done, and Cezar-Ion Adomnitei.2020.Omnidirectional Antenna with Complex Conjugate Impedance for Radio Meteor Detection. *International Conference on Development and Application Systems (DAS)*.
11. Lesanu, Cezar Eduard, and Adrian Done. 2016. Parasitic circular polarized vertical antennas. *International Conference on Development and Application Systems (DAS)*.

12. Fabrés, Marta Cabedo, et al. 2002. Novel mobile terminal antenna for meteor burst communication systems. *Microwave and Optical Technology Letters*, Volume 34.2, pp.80-83.
13. Hampton, Jerry R., et al. 2006. Urban propagation measurements for ground based communication in the military UHF band. *IEEE Transactions on Antennas and Propagation*, Volume 54.2, pp.644-654.
14. Mecklenbrauker, Christoph F., et al. 2011.Vehicular channel characterization and its implications for wireless system design and performance. *Proceedings of the IEEE*, Volume 99.7, pp.1189-1212.
15. Kirkby, Graham. 2019. Development of cubesat antenna systems for ionospheric sounding. Diss. University of Birmingham.
16. Parkinson, Bradford W., et al. 2020. Introduction, Early History, and Assuring PNT (PTA). Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications 1, pp.1-42.
17. Casanovas Ventura, Marc. 2021. Study: An Assessment on the Requirements for Deep Space Optical Communications. MS thesis. Universitat Politècnica de Catalunya.
18. Yin, Xuefeng, and Xiang Cheng. 2016. *Propagation channel characterization, parameter estimation, and modeling for wireless communications*. John Wiley & Sons.
19. Luebbers, R., and J. Schuster.1995.Site-Specific Radio Propagation Prediction Methods for Urban Environments. *Digital Communications Systems: Propagation Effects, Technical Solutions, Systems Design*.
20. Abbas, Sohail, et al. 2021. Improving security of the Internet of Things via RF fingerprinting based device identification system. *Neural Computing and Applications*, Volume 33.21, pp.14753-14769.
21. Khan, Abdul Nasir, et al. 2021. A comparative study and workload distribution model for re‐encryption schemes in a mobile cloud computing environment. *International Journal of Communication Systems*, Volume 30.16, pp. e3308.
22. Zhang, Yongjian, and Yue Li. 2022.High-Gain Omnidirectional Dual-Polarized Antenna for Sink Nodes in Wireless Sensor Networks. *Sensors*, Volume 22.3, pp. 788.
23. Chen, Xi, Hao Wu, and Guang Fu. 2022. Wideband VHF/UHF Wing Conformal Vertical Polarized Omnidirectional Antenna. *IEEE Antennas and Wireless Propagation Letter*, Volume 21.5, pp.953-957.
24. Li, Xudong, et al. 2022. A low profile wideband horizontally-polarized omnidirectional printed loop antenna. *International Journal of RF and Microwave Computer-Aided Engineering*, Volume 32.2, pp. e22980.
25. Hu, Peng Fei, et al. 2021.Electrically small, planar, horizontally-polarized dual-band omnidirectional antenna and its application in a MIMO system. *IEEE Transactions on Antennas and Propagation*, Volume 69.9, pp. 5345-5355.
26. Zhang, Yongjian, et al. 2021. Omnidirectional Dual-Polarized Antenna Using Colocated Slots With Wedgy Profile. *IEEE Transactions on Antennas and Propagation*, Volume 69.9, pp. 5446-5454.
27. Guo, Jingli, et al. 2021.A Compact Dual-Band Slot Antenna With Horizontally-polarized Omnidirectional Radiation. *IEEE Antennas and Wireless Propagation Letters*, Volume 20.7, pp. 1234-1238.
28. Chen, Xi, Hao Wu, and Guang Fu. 2022. Wideband VHF/UHF Wing Conformal Vertical Polarized Omnidirectional Antenna. *IEEE Antennas and Wireless Propagation Letter*, Volume 21.5, pp. 953-957.

29. Wen, Sichao, Yizhen Xu, and Yuandan Dong. 2021. A Horizontally-polarized Omnidirectional Antenna for LTE Applications. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*.
30. Lai, Jianjun, et al. 2021.Design of a dual-polarized omnidirectional dielectric resonator antenna for capsule endoscopy system. *IEEE Access,* Volume 9, pp.14779-14786.