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Research Article

# Design of Dual Frequency High Gain Antenna Based on Quasi-Continuous Meta surfaces

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## Abstract

The acquisition and processing of EEG and sEMG is an important task in the field of biomechanics. In order to collect bioelectrical signals, new design method of high gain antenna has become a hot topic. This paper proposes a design method of dual-frequency high-gain antenna based on quasi-continuous meta surface. By adding meta surfaces or adding slots to form quasi-continuous meta surfaces to replace the original patch radiating elements, the antenna performance is improved, and new ideas are provided for the realization of high-performance antennas. Based on the theoretical basis of the meta surface to increase the antenna gain, the quasi-continuous meta surface is loaded on the basis of the dual-frequency antenna, which improves the impedance matching of the dual-frequency antenna and at the same time increases the antenna gain. The proposed antenna design model is simulated and optimized, and the transmit antenna gain reaches 31.32dBi, and the receive antenna gain reaches 16.46dBi. The half-power beam width of the transmitting antenna is within 10°, and the half-power beam width of the receiving antenna is 36°, which fully meets the design requirements of the biomechanical signal acquisition antenna.

**Keywords:** Meta surface; High gain; Dual frequency; Antenna

## Introduction

In recent years, the concept of metamaterial has been developed very rapidly, thanks to its ability to control electromagnetic waves by using the plane structure of sub wavelength dense arrangement, which shows the electromagnetic characteristics beyond the conventional substances in nature. The permittivity and permeability of metamaterials can achieve the same positive and negative or one positive and one negative or even zero characteristics through the artificially designed subwavelength periodic structure, covering the numerical space of permittivity and permeability of materials [1]. As a two-dimensional artificial metamaterial, quasi-continuous meta surface not only has the properties of sub wavelength periodic structure, but also has the characteristics of thin thickness, low loss and easy manufacturing. It should be noted that the cell period and substrate thickness of the meta surface must be much smaller than the wavelength in free space λ [2]. With its unique ability to manipulate electromagnetic waves, quasi-continuous meta surface can be used in frequency selective surface, high impedance surface, holographic surface, perfect absorber, lens and other applications [3]. Nowadays, the artificial electromagnetic quasi-continuous meta surface can be used in a wider field of communication. However, unlike the artificial electromagnetic metamaterial, its basic element can only extend in two-dimensional plane, and cannot extend in the direction perpendicular to the surface [4]. Therefore, it is impossible to use the equivalent permittivity and permeability to describe the electromagnetic properties of artificial electromagnetic metamaterials.

For microstrip planar reflective array antenna, it mainly works in long-distance communication system and other areas with high gain requirements. At present, the main high gain antennas used in the field of communication are parabolic antenna and phased array antenna. Although the traditional parabolic antenna has the advantages of good beam directivity, high gain and wide band, its reflector is difficult to process, bulky and heavy, which limits its role in some portable fields. With the development of the concept of artificial electromagnetic meta surface, it has been widely used in antenna design [5]. Among them, the microstrip planar reflective array antenna is one of the products of the combination of quasi-continuous meta surface and antenna. This kind of antenna is composed of a space feed and a meta surface covered with radiation elements. It combines some advantages of traditional high gain antenna and overcomes the defects of the two kinds of antenna to a certain extent. By placing the quasi-continuous meta surface around the microstrip antenna, the characteristics of strong resonant impedance can be improved, and the impedance matching bandwidth and gain bandwidth can be increased. In order to realize low profile, broadband or miniaturized antenna design, microstrip line is used to feed the top meta surface through the coupling aperture of the ground plane to excite multiple modes of the antenna. Konstantinidis K et al. proposed a new design method of multilayer periodic array for broadband sub wavelength Fabry Perot antenna, and by designing a quasi-continuous meta surface structure with a three-layer double-sided periodic array at 1/6 wavelength away from the antenna, the antenna gain, and gain bandwidth are improved [6]. Moradi A et al. used the meta surface to reduce the sidelobe level of the rectangular horn antenna working in the Ku band and covered the inner wall of the E plane horn with the meta surface, adjusted the electric and magnetic field strength near the horn wall, and optimized the antenna gain to increase and the sidelobe to decrease [7].

The use of meta surfaces in the array antenna can reduce the mutual coupling between the array elements due to surface waves and improve the overall performance of the array antenna. The common coupling between wideband, dual polarized, high-density patch array antennas is reduced by using a meta surface, which is composed of a grounded capacitive load ring and a π-shape element is composed of two types of resonators, which are loaded into the array antenna. In summary, loaded meta surface can break through the structural limit of traditional materials, improve the radiation characteristics of antenna, and bring new changes to the design and development of high-performance antenna [8]. Therefore, this paper proposes a design method of array antenna based on quasi-continuous meta surface, to provide a new idea for the realization of high-performance antenna.

## Optical Properties of Quasi-Continuous Meta surfaces

Quasi-continuous meta surface is a type of metamaterial whose thickness is negligible relative to the wavelength. In the early stage, the study of quasi-continuous meta surface mainly focused on the non-resonant surface. The research objects include some complementary structures of densely arranged wires, metal strips or metal sheets. While the main content of the study is the strong anisotropy of the electromagnetic properties of these structures. In the past decade, the research of quasi-continuous meta surfaces has shifted to the quasi-continuous resonant type. Moreover, a large part of the attention is focused on the design of a series of new antennas based on quasi-continuous meta surfaces [9]. The characteristic impedance is usually used to describe the electromagnetic characteristics of resonant structure. When the working frequency is near the resonance point of the structure, the characteristic impedance of the structure is very high, showing the characteristics of artificial magnetic conductor; while when the working frequency is not near the resonance point, the characteristic impedance of the structure can be positive or negative. This shows that the meta surface can support TE and TM surface wave propagation at different frequencies [10]. This property enables the meta surface to mimic electrical and magnetic conductors with optical properties. By optimizing the structure parameters, the propagation characteristics of these surface waves can be adjusted or the conversion from surface waves to space waves can be realized. In addition, meta surface can also be used to control the transmission characteristics of space wave and realize abnormal refraction and reflection.

Data capacity is rapidly reaching its limit in modern optical communications. Optical vortex with spiral wavefront has been explored to enhance the data capacity for its unbounded quantum states of orbit angular momentum (OAM). However, traditional devices used to generate OAM carrying beams suffer from bulky size. Surface plasmon polaritons (SPPs) have created an appealing platform to design various optical components with small footprints [11]. Ultrathin plasmonic meta surfaces with phase abruptions exhibit the ability to break the traditional refraction and reflection law, which makes it possible for compact OAM generators. Guo et al. from Chinese Academy of Sciences have now proposed and experimentally demonstrated continuously shaped meta surfaces constructed by annular apertures engraved onto the silver film, which promises high purity of OAM [12]. The annular apertures are "true continuous metaatoms" and single metaatom can obtain geometric phase shift of 2π via the spin orbital interaction. The main difference with the discrete metaatoms is that the wavefront engineering accuracy is significantly improved because of their nearly infinite small "pixel sizes" and thus the phase noise can be greatly suppressed. By adjusting the width of annular apertures clockwise or anticlockwise, another scheme of continuous azimuthal phase shift, i.e., aperture width dependent plasmon phase retardation is shown. Merged geometric phase and plasmon retardation phase develops another method for arbitrary OAM generation, including integer OAM and fractional OAM, which may play a significant role in the OAM assisted dense mode division multiplexing (DMDM) systems.

Based on the conceptually new continuously shaped meta surfaces with merged phase modulation, several novel meta surfaces with a radius of 9 μm has been fabricated and demonstrated the OAM generation of $l = 1, \pm 1.5$ and $\pm 2$. Compared with the discrete counterparts, the measured purity of generated OAM reaches 90%, which is improved by nearly 50%.

## Technology of Quasi-Continuous Meta surfaces Antenna

The rapid development of metamaterials greatly promotes the rise of metamaterial antenna technology. The application of meta surface in antenna design can improve the performance of traditional antenna, such as bandwidth, directivity, radiation efficiency, front to back ratio and gain, reduce radar cross section and change polarization characteristics. This new type of antenna, which combines meta surface structure with traditional antenna, can be called meta surface antenna. In 2012, Hailiang Zhu of the University of Hong Kong designed a meta surface structure based on the square loop like meta surface, of which unit consists of a rectangular loop metal patch and a diagonal metal strip inside the rectangle [13]. Two kinds of source antennas, microstrip patch antenna and microstrip slot antenna, are used in the research. The meta surface elements are arranged in 4x4 array to cover a certain distance above the source antenna. It can convert the linearly polarized wave radiated by the source antenna into the circularly polarized wave and realize the design of the circularly polarized antenna. The meta surface placed at different positions can convert the linearly polarized wave radiated by the source antenna into the circularly polarized wave in different polarization states, as shown in Figure 1. This structure has the following advantages: a) compact structure; b) simple structure can realize the conversion from linear polarization to circular polarization; c) low cost; d) simple source antenna (patch antenna or slot antenna); e) wide bandwidth.

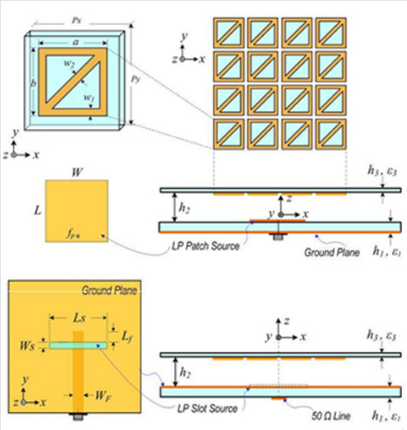


**Figure 1:** Circularly polarized antenna based on meta surface.

In 2013, Chung KL et al. proposed to combine the traditional probe fed circularly polarized slot patch antenna with ultra-thin square loop shaped meta surface to form a low-profile antenna, as shown in Figure 2. It can improve the performance of the antenna in terms of impedance bandwidth, antenna efficiency and front-to-back ratio. In 2015, Zhao Wu et al. proposed a wide-angle circularly polarized meta surface cladding antenna that can be used for satellite communications, including a meta surface composed of a rectangular metal patch array and a slot-coupled antenna [14]. The antenna can convert the linearly polarized wave radiated by the source antenna into a circularly polarized wave, and because there is no gap between the slot antenna and the meta surface, the entire antenna has the characteristics of low profile and compact structure. In 2016, Qu Shaobo's research group at Xi'an Air Force Engineering University designed a circularly polarized antenna based on a polarized rotating meta surface. The researchers have designed a reflective polarized rotating meta surface by using the slant metal strip structure, which can achieve efficient co polarization conversion to cross polarization in the working frequency band. A new polarization conversion meta surface antenna is designed by combining it with the microstrip slot antenna. The simulation and experimental results show that the working bandwidth of circularly polarized antenna is seriously affected by the distance between microstrip slot antenna and meta surface, and when the distance is adjusted, three circular polarizations working in different frequency bands can be obtained.

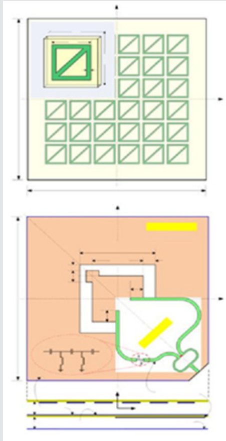

**Figure 2:** Circularly polarized antenna based on meta surface.

## Design of Dual Frequency High Gain Antenna Based on Quasi-Continuous Meta surface

### Antenna structure

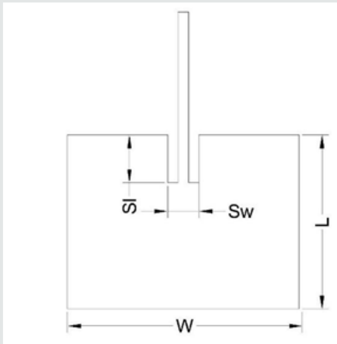


**Figure 3:** Patch unit structure.

According to the application requirements of biomechanical electrical signal acquisition, the traditional microstrip patch antenna unit cannot meet the requirements of high gain, narrow beam and low sidelobe, only by combining the microstrip patch antennas into an array according to a certain rule can the requirements be met. The working frequency of the microstrip array antenna designed in this paper is 77GHz. At this frequency, the dielectric constant of most dielectric plates will change as its loss increases, which will affect the radiation characteristics of the microstrip antenna. The microstrip array antenna is composed of microstrip patch antennas combined into an array through the feed network, so the performance of the microstrip array antenna is mainly affected by the performance of the microstrip patch antenna and the design of the feed network. In order to design a microstrip array antenna that meets the requirements of bioelectric signal acquisition, it is first necessary to design a suitable microstrip patch antenna, and then design a feed network to form an array of microstrip patch units. In the microstrip patch unit, the microstrip feed line and the microstrip patch are both on the dielectric plate, and photolithography can be used during antenna processing. As shown in Figure 3, a slot with width Sw and length Sl is dug out in the center of the wide side of the microstrip patch, the microstrip feeder is inserted into the slot to feed the microstrip patch. Since the feeding structure only has the length and width changes of the slot, the impedance of the microstrip antenna can be changed by adjusting the size of Sl and Sw to achieve impedance matching.

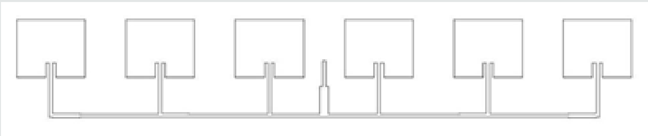

**Figure 4 : 1×6 microstrip array antenna.**

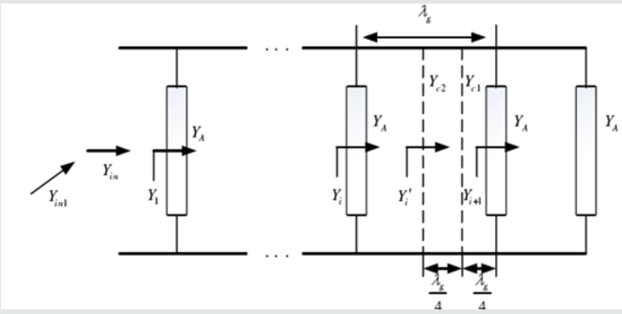

**Figure 5:** 1×6 Equivalent circuit of the feed structure of the 1×6 microstrip antenna array.

Through simulation and modeling, the optimal antenna structure parameters are L=1.05mm, W=1.38mm, Sl=0.268mm, Sw=0.256mm. In the microstrip antenna array, each element antenna realizes power distribution through an impedance matcher, that is, the input impedance of each element antenna is different. The performance of a single patch is far from being able to meet the application requirements of bioelectric signal acquisition, we need to form a microstrip array antenna from the patch antenna. We linearly connect 6 microstrip patch antennas in series with microstrip feeders to form a 1×6 microstrip antenna linear array, as shown in Figure 4. The linear array adopts series-parallel hybrid feeding, and the two sides of the linear array center adopt series feeding and the two sides are symmetrical about the center. The feed phase of each array element is equal, and the amplitude obeys the Dolf-Chebyshev distribution. T-shaped power splitters are used for parallel feeding on both sides of the linear array. The distance between each element in the linear array is an equivalent wavelength to ensure that the feed phase of the elements is equal. The impedance matching and power distribution of the entire linear array are realized by a quarter impedance matching device. The equivalent circuit of the feed structure of the 1×6 microstrip antenna array is shown in Figure 5. YA, Yin, Yin1 respectively represent the input impedance of a single patch antenna, one side of the linear array, and the entire linear array. YC1, YC2 respectively represent the characteristic admittance of the two-stage impedance matcher. Generally, the impedance matcher of YC2 section is the same as that of the main feeder. The YC1 section is the quarter impedance matcher in front of each element in the linear array structure.

## Design of Transmitting Antenna

In the antenna designed in this paper, the feeders of each linear array are equal phase sine waves, with unequal amplitude, and the current amplitude obeys Chebyshev distribution from center to end. 4-element linear array has the advantages of narrow beam and high efficiency, but also has the disadvantage of high sidelobe level; the 6-element linear array has low sidelobe level, wide 3dB beam and poor equalization. The antenna array with narrow beam, low sidelobe and high gain is obtained by adding 6-element line array before and after the planar array based on 4-element line array. The results show that the method is feasible and meets the requirements of biomechanical acquisition system for narrow beam, side lobe, high gain and low radiation characteristics. Based on 4 × 8 microstrip array, we add a 1×6 microstrip linear array at the beginning and the end to reduce the side lobe. The radiation gain diagram of the microstrip array antenna is shown in Figure 6(a). The gain is at frequency 77GHz. The half-power beam width of the E and H plane radiation patterns of the microstrip array antenna are 9.25° and 9.34°, respectively. The antenna radiation gain is 31.32dBi, and the sidelobe levels of the E and H plane radiation patterns of the microstrip array antenna are -21.69dB and -20.47dB, respectively. Figure 6(b) is standing wave of the transmitting antenna. In can be seen that the working frequency of the transmitting antenna is 76.89GHz, and at this time, and working bandwidth is 0.46GHz. As shown in the standing wave diagram of microstrip array antenna, in the working frequency band of the antenna, the standing wave is less than 2. The transmitting antenna can be used for beam scanning, and its maximum design scanning angle is 48°.

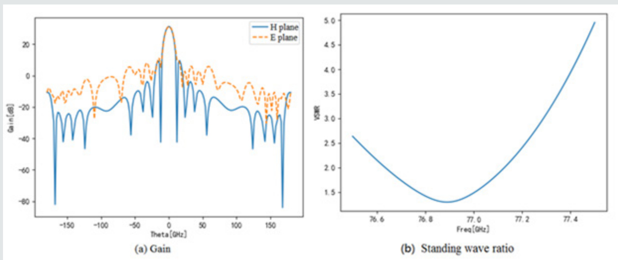


**Figure 6:** Radiation performance diagram of microstrip array antenna.

## Design of Receiving Antenna

The main function of biomechanical signal acquisition system is to collect bioelectrical signals. In general, the phase difference between the two received signals needs to be obtained in order to obtain the bio conductive signal, which is then obtained by digital processing, so it requires that the front-end antenna needs at least two receiving antennas to receive the electrical signals transmitted back and forth by biological tissues. In this paper, a dual receiving antenna structure, namely multi-channel design, is adopted. Since both transmitting antenna and receiving antenna can radiate electromagnetic wave, the influence between antennas should be minimized in the design. According to the radiation theory, the farther the distance between the components, the smaller the mutual influence, so increasing the distance between the transceiver antenna is the most simple and practical method. In the practical application of biomechanical signal acquisition, the detection system not only needs to detect a single signal source, but also needs to detect a certain range of signals, which requires the receiving antenna to have a certain beam width. From the above simulation design, the linear array can obtain a wide E-plane beam width. Secondly, the receiving antenna needs to receive the electromagnetic wave reflected from the target obstacle, and its gain is generally not less than 15dBi. In this paper, 2×6 microstrip antenna array is used as the receiving antenna, as shown in Figure 7. In can be seen from the figure that, the design method of the receiving antenna is similar to that of the transmitting antenna, which can be obtained by using the two 1×6 microstrip antenna linear arrays designed above in parallel. Microstrip antenna linear array adopts Dolf-Chebyshev distribution for equal phase and unequal amplitude feed. The distance between each element is equivalent wavelength. We model and optimize the designed receiving antenna model in simulation software and obtain the radiation pattern when the receiving antenna structure is optimal, as shown in Figure 8(a). Microstrip array antenna standing wave pattern is shown in Figure 8(b), within the working bandwidth of the antenna, the standing wave is less than 2.

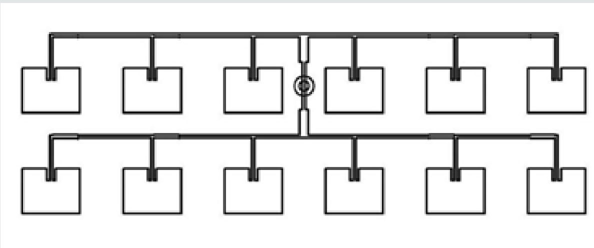

**Figure 7:** Radiation performance diagram of microstrip array antenna.

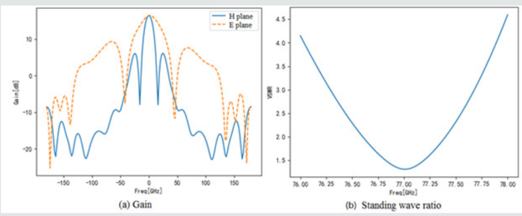


**Figure 8:** Radiation performance diagram of microstrip array antenna.

## Simulation Analysis

### Performance Analysis

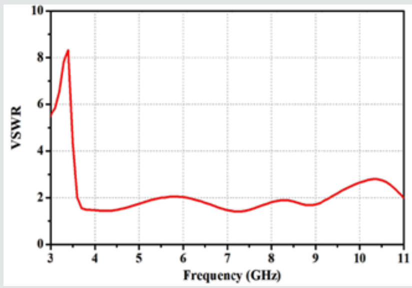


**Figure 9:** Simulation results of the designed antenna standing wave ratio.

The simulation results of the voltage standing wave ratio (VSWR) of the meta surface-based antenna designed in this paper as a function of frequency are shown in Figure 9. It can be seen from the figure that the working bandwidth of the antenna (VSWR<2) ranges from 3.61GHz to 9.26GHz, relative bandwidth is 87.8%, center frequency as f0=6.427GHz, then the overall size of the antenna is 0.641λ0×0.731λ0×0.018λ0. Thanks to the feed structure design of microstrip line to slot line conversion, the broadband single ended emitter directional antenna based on meta surface achieves good impedance matching in the bandwidth range. According to the simulation results of the antenna gain in the end fire direction, the actual gain of the antenna varies from 5.32dBi to 8.82dBi in the working bandwidth. The highest gain is 8.82d Bi when the operating frequency is 8.7GHz. The 3dB gain bandwidth ranges from 5.96GHz to 9.26GHz, and the 3dB gain fluctuates from 5.82dBi to 8.82dBi. The radiation efficiency of the antenna is more than 85% in all operating bandwidth. Although the actual gain of the antenna from 9.26GHz to 9.78GHz ranges from 7.66dBi to. 32dbi, the gain is still very high and fluctuates in an acceptable range, but the radiation pattern of the antenna is distorted at high frequency, and good impedance matching cannot be obtained.

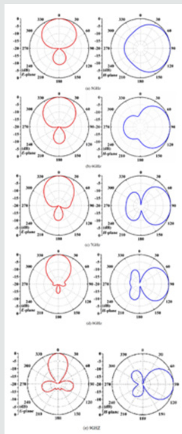

**Figure 10:** Normalized radiation directions of E-plane and H-plane of array antenna.

The normalized radiation directions of E-plane and H-plane of array antenna based on meta surface at the six frequency points of 5GHz, 6GHz, 7GHz and 8GHz are shown in Figure 10. In the figure, the red and blue solid lines indicate the main polarization of the antenna; the red and blue dotted lines indicate the cross polarization of the antenna. The two-dimensional patterns of E-plane and H-plane show end shooting phenomenon. It can be seen that when the antenna works at 5GHz, 6GHz, 7GHz,8GHz and 9GHz, the cross-polarization level is very low, and it is better than -20db at these five frequency points. In the bandwidth range, with the increase of frequency, the beam of E-plane and H-plane radiation pattern of wideband single emitter directional antenna based on meta surface will gradually narrow. The radiation pattern of the antenna keeps good directional radiation characteristics and obtains good front to back ratio, and its radiation direction is towards the direction of surface wave propagation.

## Working Mechanism Analysis

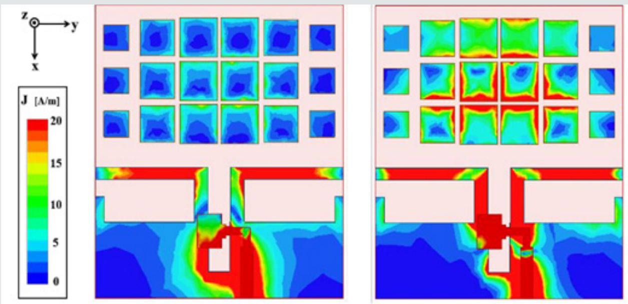


**Figure 11:** Simulated surface currents distribution density of the proposed antenna.

The thickness of the dielectric plate used in the designed antenna is 0.127mm, the relative dielectric constant is 3 and the loss tangent is 0.0013. In the rectangular microstrip patch, the width is 1.38mm and the length is 1.07mm. The simulation results of the surface current distribution density of the proposed antenna based on the meta surface are shown in Figure 11. The figure shows the current distribution density of the antenna at 4GHz at low frequency and 8GHz at high frequency. The comparison shows that the current distribution density of the microstrip to slot transition structure and the driving dipole structure is very large at 4GHz or 8GHz, because these two parts belong to the surface wave transmitter. Compared with the traditional Yagi antenna structure, the refractive index modulated meta surface structure actually belongs to the director of the antenna, which guides the surface wave to propagate along the - X axis. It can be seen from the figure that the energy of the modulated meta surface composed of subwavelength periodic patches is concentrated between the gaps of the patches. Moreover, the surface current of the end fire antenna based on the meta surface at 4GHz is much less than that at 8GHz. Therefore, it can be inferred that the meta surface structure with modulated refractive index plays a key role in high frequency, that is, it plays a good role as a director. In addition, the modulation refractive index patch can be used to compensate for the inconsistency of dipole current at high frequency, not only to improve the antenna gain in the direction of end firing, but also to expand the width of the antenna.

## Parameter Analysis

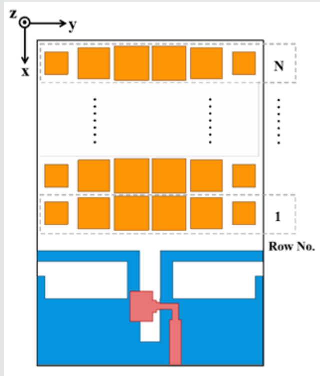


**Figure 12:** Notation of the patch array of the wideband meta surface antennas.

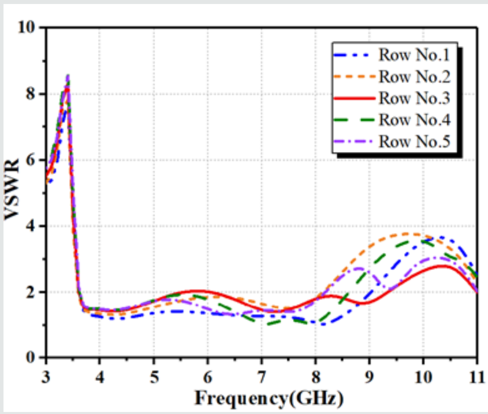


**Figure 13:** Simulated results of VSWR of the meta surface-based antennas.

The schematic diagram of the patch array of the wideband proposed antenna based on the meta surface is shown in Figure 12. In the figure, N is the number of rows of the modulated index meta surface, which ranges from 1 to 5. When N ranging from 1 to 5, the simulation curve of VSWR of wideband single ended fire directional antenna based on meta surface is shown in Figure 13. It can be seen from the figure that the low frequency matching point (VSWR=2) of the frequency band of the modulated index meta surface changes around 3.6GHz regardless of the number of rows. It can be concluded that the change of the number of lines of the modulated meta surface has no obvious effect on the performance of the low-frequency matching points but has a great influence on the high-frequency matching points. The simulation diagram of the gain versus frequency of the proposed wideband single emitter directional antenna is shown in Figure 14. It is not difficult to find that the first local gain peak moves towards low frequency with the increase of N. Within the bandwidth range from the low-frequency matching point 3.6GHz to the frequency point of the first local gain peak, as N increases, the average gain also increases. This phenomenon shows that the number of rows of the modulated refractive index meta surface has a great influence on the gain curve of the antenna, and the gain increases with the increase of the number of meta surface patch lines. When the first local gain peak is reached, as the frequency increases, the gain curve shows a downward trend. It should be noted that when the number of lines of the meta surface patch increases, it also means that the overall size of the antenna will also increase. Therefore, when designing a broadband single-ended directional antenna based on a meta surface, it is necessary to balance the relationship between antenna radiation performance and antenna size, so as to ensure the antenna's high performance, broadband and miniaturization characteristics.

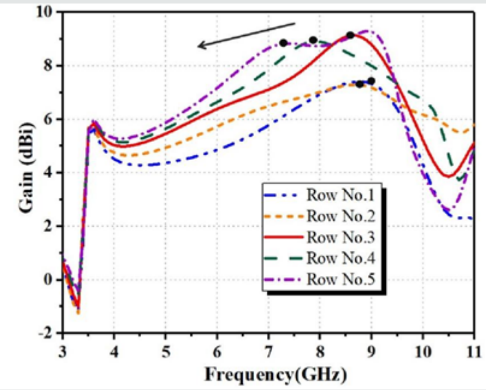


**Figure 14:** Gain versus frequency of the proposed wideband single emitter directional antenna.

## Conclusion

The existing dual-frequency antenna structure has different shortcomings, such as the working frequency band is difficult to tune, the gain is not high enough, increasing the antenna gain will affect the antenna resonance frequency and matching level, or fail to provide the specific antenna design process and implementation method. This paper proposes a design method of dual-frequency high-gain antenna based on quasi-continuous meta surface, which is composed of three parts: the transition structure from the microstrip line to the slot line as the feeder, the dipole as the feeder, and the modulated refractive index meta surface as the guide surface wave propagation part. By adding meta surfaces or adding slots to form meta surfaces to replace the original patch radiating elements, the antenna performance is improved, and new ideas are provided for the realization of high-performance antennas. Based on the theoretical basis of the meta surface to increase the antenna gain, the quasi-continuous meta surface is loaded on the basis of the dual-frequency antenna, which improves the impedance matching of the dual-frequency antenna and at the same time increases the antenna gain. The proposed antenna design model is simulated and optimized, and the transmit antenna gain reaches 31.32dBi, and the receive antenna gain reaches 16.46dBi. The half-power beam width of the transmitting antenna is within 10°, and the half-power beam width of the receiving antenna is 36°, which fully meets the design requirements of the biomechanical signal acquisition antenna.

Finally, using the number of patch rows of the modulated refractive index meta surface as an independent variable, the change law of its VSWR curve and gain curve was analyzed parametrically. The antenna's working bandwidth is 3.61GHz to 9.26GHz, and its relative bandwidth has reached 87.8%. In the ultra-wideband range, the antenna gain is maintained between 5.82dBi and 8.82dBi, and its 3dB gain bandwidth is 5.96GHz to 9.26GHz, and the relative bandwidth is 43.4%. The dipole antenna is used as the feed of the modulated meta surface antenna, and the meta surface is used to guide the propagation of surface wave unidirectionally. The antenna has the characteristics of single shot, wide working frequency band and high directivity, and the single shot pattern is well maintained in the bandwidth range.

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