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A Reflective Metasurface to Generate Vortex Beam Carrying Orbital Angular Momentum for C-band Applications

C-bant Uygulamaları için Yörüngesel Açısal Momentum Taşıyan Girdap Işını Üreten Yansıtıcı Bir Meta Yüzey

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C-BANT UYGULAMALARI İÇİN YÖRÜNGESEL AÇISAL MOMENTUM TAŞIYAN GİRDAP IŞINI ÜRETEN YANSITICI BİR META YÜZEY

ÖZ

Bu makalede, belirli bir frekansta veya frekans aralığında elektromanyetik dalganın faz kontrolörü olarak kullanılabilecek yeni bir birim hücre önerilmektedir. Sunulan birim hücre 6GHz'de kare bir halkanın çapına paralel olarak uzunluğu 1 mm ile 9 mm arasında değişen iki saplama ile tasarlanmıştır. İstenilen frekansta bir girdap demeti sağlayan yansıtıcı antenin tasarımı için açıklık verimliliği hesaplamaları yapılmış ve analiz edilmiştir. Tam dalga benzetimi kullanılarak 1. ve 2. modlarda yörüngesel açısal momentum üreten iki yansıtıcı anten gerçeklenmiş ve doğrulanmıştır. Benzetim sonuçları, sunulan yansıtıcı antenin bir OAM (yörüngesel açısal momentum) ışını üretmek için iyi bir performans gösterdiğini ortaya koymaktadır.

Anahtar Kelimeler: Vorteks Işını, Yörüngesel Açısal Momentum, Meta Yüzey, Yansıtıcı Dizi, Faz Dağılımı.

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A REFLECTİVE METASURFACE TO GENERATE VORTEX BEAM CARRYİNG ORBİTAL ANGULAR MOMENTUM FOR C-BAND APPLİCATİONS

ABSTRACT

In this letter, a novel unit cell is proposed which can be used as a phase controller of the electromagnetic wave at a specific frequency or a range of frequencies. The presented unit cell is designed at 6GHz with two stubs whose length changes from 1 mm to 9 mm parallel to the diameter of a square ring. For the design of the reflectarray antenna providing a vortex beam at the desired frequency the calculations of aperture efficiency have been performed and analyzed. By using full-wave simulation two reflectarrays producing orbital angular momentum with modes 1 and 2 have been implemented and verified. The simulation results demonstrate the good performance of the presented reflective antenna to generate an OAM (orbital angular momentum) beam.

Keywords: Vortex Beam, Orbital Angular Momentum, Metasurface, Reflectarray, Phase Distribution

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1. INTRODUCTION

Boosting the capacity of transmission channels has always been one of the main concerns in wireless communication systems. Among the methods used to increase channel capacity, the concept of orbital angularity (OAM) has recently received much attention due to its inherent potential in orthogonality between modes. According to theory, the mode numbers are infinite so this causes a tremendous valency that can be exploited. This feature of a wave-bearing orbital angular momentum makes it possible to use several modes simultaneously at a given frequency, thus improving the capacity of the transmission channel without allocating more bandwidth. Compared to plane waves, vortex waves bend along the wavelength, the number of bends in a wavelength is called the mode number, denoted by l in OAM. These bends are erected by adding an exp(jlϕ) component to phase distribution and cause a spiral wavefront. Since 1992, when Allen et al [1] discovered that light can bear orbital angular momentum, much research has been conducted in the field of optics and physics, and many articles have been published. In 2007 [2], the concept of OAM struck in wireless communication systems, and then various techniques were used to produce orbital angular momentum in the microwave frequency domain. Amidst the most common ones, we can refer to Spiral phase plates [3-4], uniform circular array antenna (UCA) [5-6], and Reflectarray antenna [7-8].

Betwixt the extant methods to obtain high gain and sufficient efficiency antennas, the use of reflectarray antennas is an appropriate choice due to their light, flat, and cost-effective structure. Reflectarray antennas are a combination of reflector an- antennas and array antennas [9]. Their theory is based on the phase distribution of the reflectarray aperture that should be analogous to the phase distribution of the reflector aperture [9]. A reflectarray is comprised of some printed elements on a planar plate (substrate) which form an array, another antenna by eradiating the wave towards the mentioned plate operates as a feed antenna for reflectarray. Each element is designed so that when it is exposed to wave radiation by the feeding antenna, it reflects the wave with a different phase relative to the other elements. Therefore, the phase distribution created on the aperture should be so that the reflection waves from all the elements are in phase in a specific direction. Moreover, the analysis and design of reflective elements, which are usually known as phase elements [9], is of great importance. The design of an OAM reflectarray can be divided into two parts: unit cell design and full structure design. In the following sections, these steps are examined in detail.

2. MATERIALS AND METHODS

To analyze the reflective metasurface, the full-wave simu- lation stemmed from the finite-element method was used [8]. We have proposed a unit cell that is printed on the top layer of Rogers RO4725JXR dielectric and its thickness and εr are 1.5 mm and 2.64, respectively. A ground layer is placed 1.5 mm away from the back side of the substrate. Fig.1 shows the structure and dimension of the unit cell. As can be seen, the unit cell's period is 20 mm. Two variable stubs are stuck to two stable stubs and those stable stubs are bound to opposite corners of a square ring. The length of variable stubs changes along diametrical.

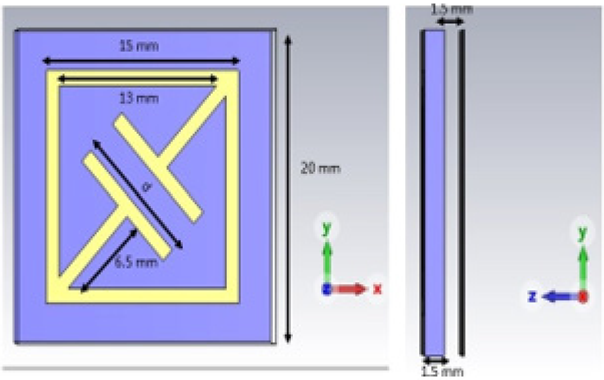


Figure 1. Top side and right side views of the unit cell structure

By variation of stub lengths from 2 mm to 9 mm a phase range of 310° is obtained that is sufficient to design a reflectarray The proposed frame is designed to work in the C-band with an operating frequency of 6 GHz. Design parameters have been optimized to have a linear phase response in the desired frequency band. In Fig.2 S-parameter results are demonstrated. The magnitude of s- s-parameters is small and in the range of -1 dB to 0. This means the structure can operate as a good reflective and has low reflection losses. For three diverse frequencies, the phase variations are depicted in Fig.3 which shows the responses are approximately parallel means this structure can act as a broadband antenna. Fig.4 displays the phase response to different values of air gap between the dielectric and ground plate. The main aim of this air gap is the creation of a more linear curve for s-parameters which causes less phase error in reflectarray design. As it is shown in Fig.4 we achieved more phase range and a linear curve for hair =1.5 mm.

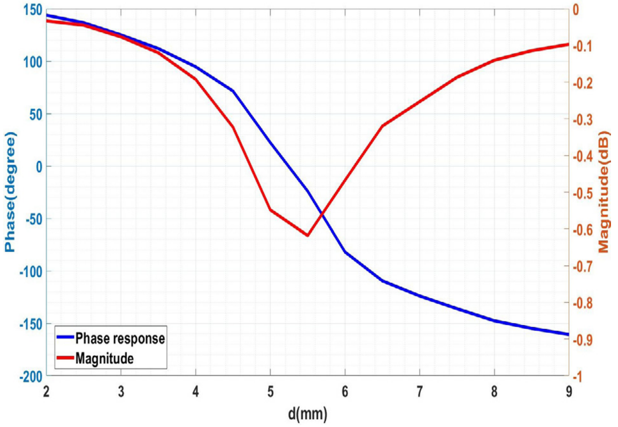


Figure 2. Phase response and Magnitude of the unit cell

3. OAM REFLECTARRAY INVESTIGATION

The first step to designing a reflectarray antenna is cal- calculations of aperture efficiency [10] in operating frequency. A square aperture with 18*18 elements on it and a length of 7.5λ_0 is proposed. Aperture efficiency calculations were done. According to Fig.5, the best range for the q factor of the feed antenna and the best range of the distance in the far-field zone of the feed antenna to the aperture surface were determined.

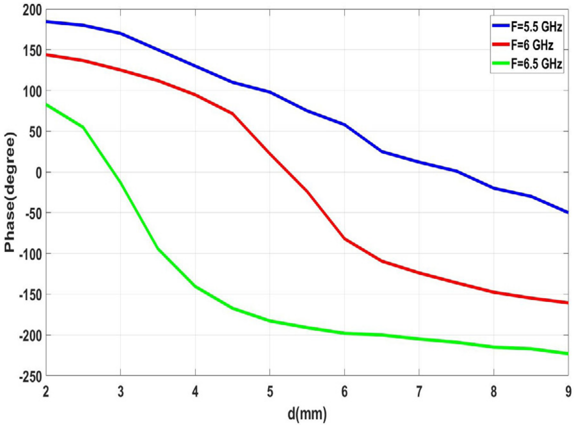


Figure 3. Phase response in three different frequencies

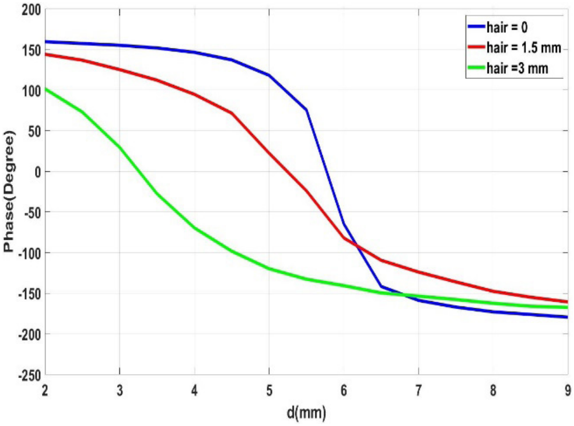


Figure 4. Phase response variation to different values of ta(air gap)

As Fig.6 and Fig.7, We chose q=5 and H=6.2λ which in this case the aperture efficiency is gained by 74%.

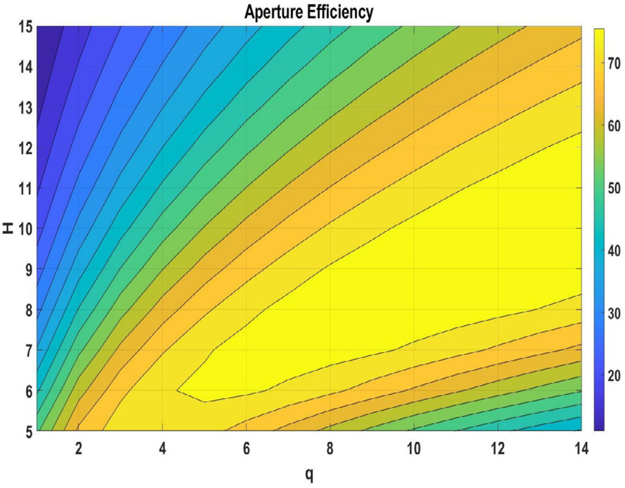


Figure 5. Obtained Aperture Efficiency

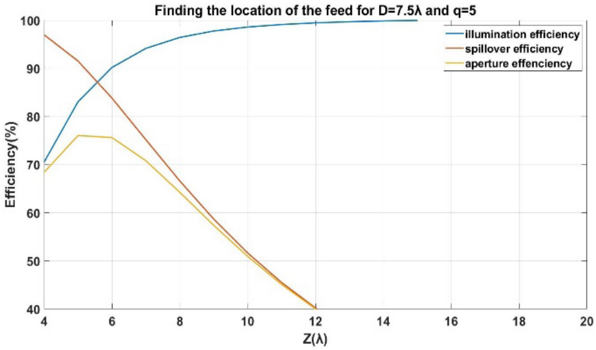


Figure 6. Obtained Aperture Efficiency

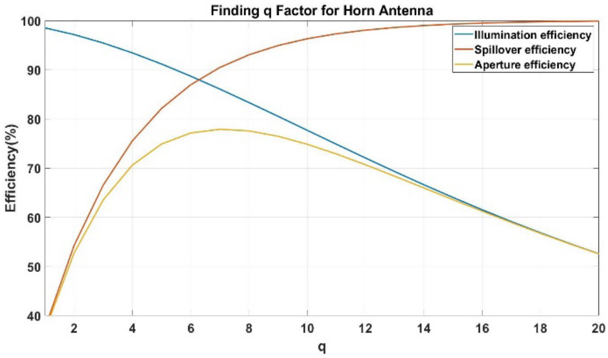


Figure 7. Selecting the q factor of the feed antenna

The next step is to determine the feed. For the obtained q factor based on directivity calculations, as shown in Fig. 8, the desired directivity is 12 dB. We designed a horn antenna in 6 GHz which has 12 dB gain, and its characteristic reflection coefficient is demonstrated in Fig.9. The phase distribution by using Eq.1 on the square aperture with 324 unit cells for the -2, -1, 1, and 2 modes are calculated and plotted in Figure 10.

$$\emptyset_{mn}^{c}=l\emptyset_{mn}-k_0*\left[\left|r_{mn}-r_f\right|+r_{mn}\cdot\hat{u}_0\right] \quad (1)$$

$$l=0,\pm1,\pm2,\ldots$$

$$\emptyset_{mn}=artan\left(\frac{y}{x}\right) \quad (2)$$

In this equation, $\overrightarrow{r_{mn}}$ is the location vector of the mnth element on the aperture,and $\overrightarrow{r_f}$ is the position vector [8] of the feed source. K_0,$\hat{U}_0$,$\emptyset_{mn}$ and l are propagation constant, desired direction to have OAM beam, azimuthal angle of mnth element on the reflectarray, and mode number, respectively. The full structure of the OAM reflectarray for mode 2 and the designed feed source are implemented in CST studio. Fig.11 depicts these structures.

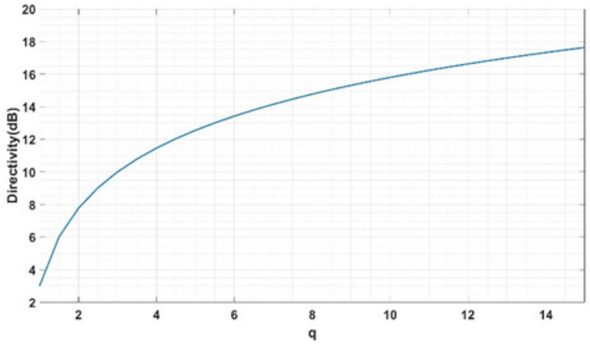


Figure 8. Finding a suitable feed antenna as calculated q factor of the feed antenna

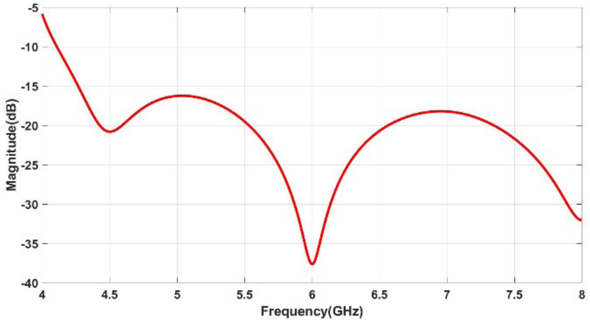
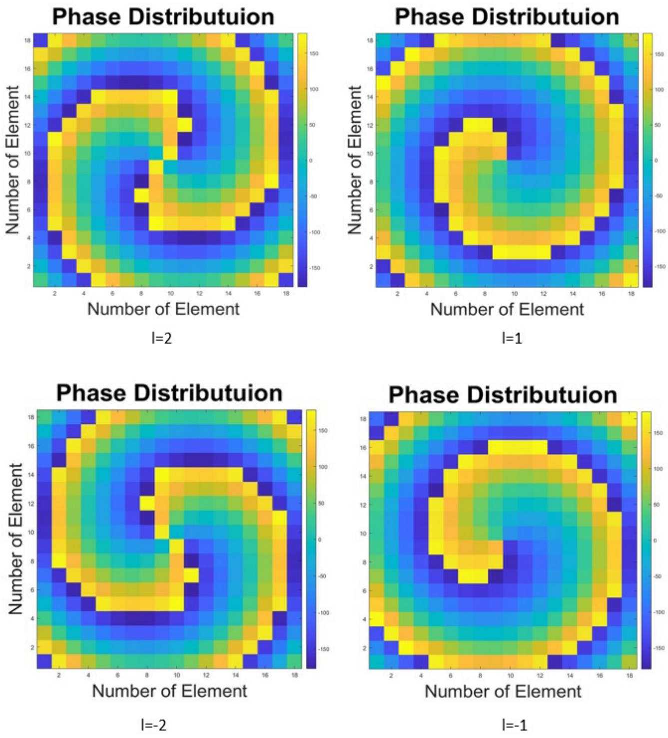


Figure 9. S-parameter result of chosen horn


Phase Distributuion
Phase Distributuion
Phase Distributuion
Phase Distributuion

l=2

l=1

l=-2

l=-1

Figure 10. Phae distribution for different modes

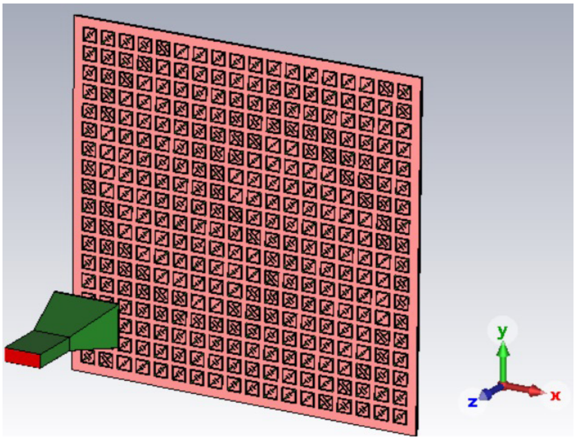


Figure. 11. Perspective view of proposed OAM-Reflectarray and Feed source antenna

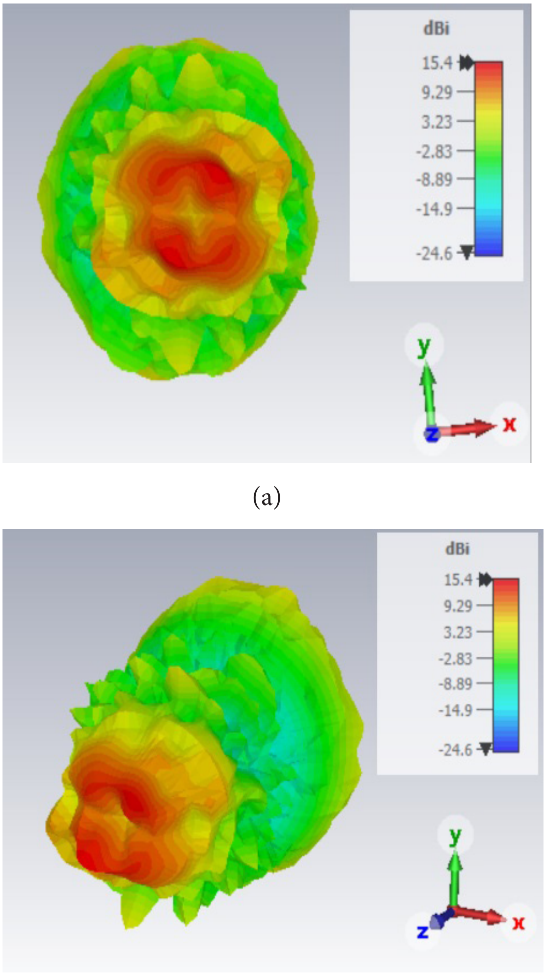


Figure 12 (a) Top view (b) perspective view of 3D radiation pattern in far-field

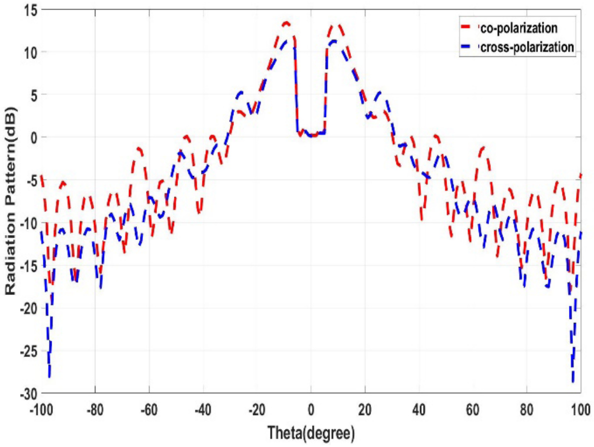


Figure 13. Simulated far-field radiation pattern of OAM-reflectarray for Mode 2

Simulation results for the presented OAM-reflectarray are depicted in Fig.12 and Fig.13. It is seen, that a null exists in the radiation pattern which means a vortex beam carrying OAM with mode 2 is generated successfully. Furthermore, the gain of the antenna is 15.4dBi.

4. CONCLUSION

In the presented paper, we investigated aperture efficiency to design an OAM-reflectarray antenna at 6GHz. Suggested metasurface unit cell performance examined to create a sufficient phase range that is needed to design. An OAM-reflectarray antenna with mode 2 was simulated and the results presented that show we could effectively generate a vortex beam with 15 dB gain.

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