ANISOTROPIC FRACTAL METASURFACE-BASED ANTENNA WITH CONTRARY BEAMS

Tanan Hongnara, Sarawuth Chaimool, and Prayoot Akkaraekthalin

Wireless Communication Research Group, Electrical and Computer Engineering, King Mongkut’s University of Technology North Bangkok, Thailand; Corresponding author: jaounarak@gmail.com

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ABSTRACT: The capabilities of the dual-band bidirectional dipole antenna to couple near-field with the metasurface have been investigated both numerically and experimentally. By properly positioning the radiating element with respect to the metasurface, the proposed antenna can emit in forward or in the backward direction. It is shown that the array of fractal closed ring resonators formed as the anisotropic metasurface can be excited to generate the opposite angular beams even though the reflection coefficient of the metasurface is high with the same value of 0.8. This is due to the fact that the conversion of evanescent to propagation waves from transmitting closely antenna to the far-zone existed. To our knowledge, this is the first report for a metasurface applied to dual-band antenna with contrary beams. This proposed metasurface-based antenna concept may present new opportunities in the design of multifunctional antennas. © 2017 Wiley Periodicals, Inc. Microwave Opt Technol Lett 59:715–720, 2017; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.30378

Key words: metamaterials; near-field coupling; evanescent-to-propagation; opposed beams; multi-functional antenna

1. INTRODUCTION

Recently, extra-thin metamaterials or metasurfaces have been much attention generated due to their strong manipulation of electromagnetic (EM) wave and also their easy fabrication compared with bulky metamaterials [1]. Usually, the design of metasurfaces requires the computation of scattering parameters or reflection–transmission coefficients of a unit cell excited by a uniform plane wave. The incident plane wave can be decomposed as a combination of Transverse Magnetic (TM) and Transverse Electric (TE) modes with respect to the plane wave of the surfaces. As obtained, the properties of these metasurfaces are described in terms of effective permittivity and permeability [2,3], electric and magnetic surface susceptibilities [4,5], and surface reactance (impedance) [6–8]. In addition, due to the planar and thin configuration, they can realize anisotropic and extreme constitutive parameters governed by the orientation of their unit cell structures [9,10]. More recently, the strong interaction between EM waves and the metasurface has been a topic of considerable interest. Nevertheless, these considered models can only predict just the far-field characteristics, the near-field behaviors are not considered. In the other words, the basis of conventional plane wave excitation may not be representative of the actual behavior of such structure. Since the conventional Floquet-Bloch theory cannot be applied directly in near-field regions, therefore, the interaction between a vicinity radiating elements and the gratings was investigated and explored using the dyadic Green’s function [11,12]. In addition, several metasurfaces-based devices such as lens [3,13] and hologram [7], require complicated setups especially in the near-field region, so the coupling between the metasurface and surrounding structures cannot be neglected.

One of the most metasurface applications is antenna and wave propagation. Because of its planar structure, the metasurface can be integrated with printed antennas to ameliorate performances, for example, bandwidth increment, directivity, and gain improvements [14], polarization conversion [15], and radiation efficient enhancement [16]. For conventional multiband or wideband antenna design cooperated with metasurfaces, the radiation patterns of all frequency bands point out the similar directions. For instance, when we place the antenna beneath the metasurface without the ground plane or reflector, the direction of the radiation patterns towards and can pass the metasurface, therefore it will act as the meta-lens [3,13] whereas the reflector-like with highly reflection coefficient redirects the wave in the opposite direction. Moreover, when using the reflecting type of the metasurface and backed by the metallic ground plane is cooperated design, it can be formed in Fabry-Perot antenna, which it has high directivity [17].

Until now, the fractal technique is demonstrated as a useful development in microwave and antenna designs. There are two main advantages of fractal technique including miniaturization and multiband functionalities, so several researchers have applied fractal techniques for antenna design. Especially at the low frequency, one of the possible ways of decreasing unit cell size and periodicity and creating multiband operation is to use the fractal concept [18]. In addition, it not only makes the miniaturized unit cell size and periodicity but also its responds stable to a change in the incident angle from an incoming plane wave.

Nevertheless, it is worth nothing that most of them demonstrated so far, can achieve the mono-function based on either transmission or reflection and operate in a single frequency band. Unfortunately, there is little research focusing on the design of multi-function and multi-frequency operations [19]. In this paper, we demonstrate that the applications of the dual-band dipole antenna based on a metasurface to achieve opposed beam simultaneously at two different closed frequencies against both points are pretty high and the same level of the reflection coefficient response. The proposed metasurface is initially constructed as an array of square closed ring resonators (SCRRs). Then, Minkowski fractal pattern is applied in SCRR to miniaturize it. According to investigate the interaction between the radiating element and the metasurface, the dual-band printed dipole is excited as a primary source placed nearby the metasurface. At both chosen frequencies, they have the same value of reflected coefficient located below and above the resonant frequency of the metasurface. It is remarkable that although these points are equal, the peak beams of the proposed antenna are opposite directions. In other words, the beam of the lower frequency can pass the metasurface, but the other is reflected. This state is extraordinary compared with the conventional frequency selective surface that the reflection coefficient is highly and identical, the considered incident waves will be reflected. Details and mechanism will be provided in the next sections. Some preliminary simulated results were discussed by ours in [20], therefore we extend and provide an in-depth insight into the behavior of the anisotropic metasurface, and especially the effect of near-field interplays between the radiating element and metasurface, which are closely located to each other. To the best our knowledge this is the first report of the contrary beam antenna using metasurface.

2. CONFIGURATION AND METASURFACE CHARACTERISTICS

Figure 1 depicts the configuration and concept of the proposed metasurface-based antenna. It consists of a dual-band dipole antenna as a primary source and the fractal ring metasurface. The designated antenna is dual-band operation using an asymmetric fork dipole antenna (AFDA), which its longer arms ($L_1$) generate the lower resonant frequency whereas the other ($L_2$) is related to the higher frequency. Here, each arm has
approximately the shape of a half-wavelength dipole with $L_1 = 20 \text{ mm}$ and $L_2 = 18 \text{ mm}$. The AFDA is designed and built on an FR-4 substrate with a thickness of 1.6 mm, relative dielectric constant $\varepsilon_r = 4.2$, and $\tan \delta = 0.019$. It is arranged to parallel and close to the metasurface with a separation distance $d_a$.

To meet the objectives, the design of a multi-functional and multi-frequency of the fractal metasurface has been presented. The fractal loop resonator is constructed by an iterative procedure from the starting geometry of a square as shown in Figure 2(a). Therefore, the SCRR is chosen to be the initial structure of a unit cell in this design, which was theoretically studied and measured in [14,21]. Besides, this SCRR can be considered as a loop type resonator according to frequency selective surface design which is cooperated with plane wave propagation. However, in metasurface aspect, the periodicity of the unit cell ($p_x$ and $p_y$) is the significant factor that refers to the subwavelength resonator size in engineered metamaterial. It should be as small as possible when compared with wavelength at operating frequency. Then, we use the Minkowski fractal generator with $A = 18 \text{ mm}$ [Fig. 2(a)-left] applied to each side of SCRR unit cell to decrease the resonant frequency and periodicity. Unfortunately, the fractal generator can be only reached to the second order as referred to Figure 2(a)-right due to the limitation of our etching procedure. Its size is calculated and given of 18 mm $\times$ 18 mm with a copper line width of 1 mm. The periodic distance of 20 mm is equal both $x$- and $y$-axes ($p_x$ and $p_y$) that its guide wavelength at the resonant frequency (at 2.15 GHz) of the second iteration is 0.08 kg smaller than 0.105$k_0$ (at 2.95 GHz) of the zero iteration as compared in Figure 2(b), resulting in the 25% of periodicity size reduction. Finally, according to a compact size of the whole antenna, an array of $4 \times 4$ cells is symmetrically mounted at the center of the FR-4 substrate ($\varepsilon_r = 4.2$, thickness = 0.8 mm and $\tan \delta = 0.019$). The overall size of the proposed metasurface is 100 mm $\times$ 100 mm $\times$ 0.8 mm.

To obtain and compare characteristics of the conventional and proposed fractal square ring resonators, we model and analyze using commercial software CST Microwave Studio [22]. Figure 2 (b) shows the magnitude and phase of reflection responses for three iteration orders (0th, 1st, and 2nd) with normal incidence. It is clearly seen that their responses are a band-stop behavior that all peaks are nearly unity, but different resonant frequencies. As shown in Figure 2(b), thus, all metasurfaces are reflective operating as the bandstop surface. They were decreased when the fractal iteration increased that means the applied fractal concept makes the longer electrical length of the resonator, resulting in the reduction of the resonant frequency. However, when the fractal generator is applied to the unit cell, its quality factor ($Q$) will increase together with the decreased resonant frequency that means the bandwidth is reduced. The 3-dB bandwidth related to $Q$ of the smallest unit cell is narrower compared with the convention one. It means that two opposed points located middle of the resonant frequency of the second order are adjacent. Therefore, we chose these frequencies $f_1$ and $f_2$ shown in Figure 2(c)] to examine and investigate the extraordinary behavior of the metasurface. Besides, the dualband antenna is designed to correspond and excite these frequencies.

In the context of this study, we pay particular attention to the radiation pattern corresponding to the far-field radiation profile. To investigate the extraordinary of the metasurface, we chose a pair of frequencies of 1.65 GHz and 2.57 GHz as shown in Figure 2(c), which are below and above the resonant frequency of 2.15 GHz and both have the same value of reflection coefficient of 0.80 whereas the phases are different of $+150^\circ$ and $-150^\circ$, respectively. At these points, it is observed that the reflection coefficient is quite high, which acts as reflective
surface. Normally, when a radiating element is positioned underneath the reflective metasurface, the incident wave from EM source is reflected by the metasurface, which acts as an efficient reflector. Surprisingly, based on [12] and our previous numerical investigation [20], the closely spaced antennas with specific distance on the metasurface can converse the evanescent to propagative wave in free space.

3. RESULTS

In the discussion presented above, the AFDA and metasurface were fabricated and tested as shown in Figure 3. The distance between the dual-band dipole and the metasurface can be controlled and kept via four plastic screws equivalent to air at both operating bands. The AFDAs with and without metasurface were compared for both input impedance and radiation performances. The input impedance was measured by a Rohde & Schwarz vector network analyzer NVB Z20. Figure 4 illustrates the comparison of $|S_{11}|$ results of simulation and measurement of the AFDA with and without metasurface. It is seen that the simulated and measured results are in the same tendency for the both cases. We also note that the $|S_{11}|$ does not seriously affect on the input impedance performance after adding metasurface.
The measured resonant frequencies of the AFDA with metasurface are 1.65 GHz and 2.57 GHz corresponding to the two operation modes. It is only the lower band slightly shifted upward when the metasurface is placed above it. Moreover, the slightly shifted frequency in the higher band is observed between simulated and measured results in the case of the AFDA with the metasurface.

Radiation characteristics of the proposed antenna have also been investigated and measured. The simulated and measured results of the radiation patterns at 1.65 GHz and 2.57 GHz are shown in Figures 5 and 6 that the two frequencies actually refer to the expected operation modes. Figures 5(a) and 5(b) depict the calculated three-dimension (3D) radiation patterns. The characteristics of the AFDA without the metasurface in 3D and 2D show a conventional dipole-like radiation pattern, comparable forward ($\theta = 0^\circ$) and backward ($\theta = 180^\circ$) radiated gain. Obviously, two broadside unidirectional patterns are achieved with opposed direction. As it shown, the direction of maximal radiation at 1.65 GHz is pointing toward $\theta = 0^\circ$, while it is pointing toward $\theta = 180^\circ$ at 2.57 GHz. With the identical metasurface and the fixed separation distance of $d_a = 20$ mm, the radiation of both frequency bands are pointing to forward scattering (positive $+z$ direction) and backward scattering (negative $-z$ direction) with improving the gain, respectively. At 1.65 GHz, the radiated energy in far-field is peaked at $\theta = 0^\circ$ ($+z$) and the back lobe at $\theta = 180^\circ$ ($-z$) is reduced as the front lobe slightly increased when compared with the AFDA alone. On the other hand, the radiating wave of the AFDA is reflected from the metasurface at 2.57 GHz, resulting in the peaked beam at $180^\circ$. It has the more increased energy in the adverse direction of metasurface. The peaked antenna gains are probed with 4.32 dBi at 1.65 GHz and 3.91 dBi at 2.57 GHz in forward and backward directions, respectively. Briefly, when compared with the identical dual-band antenna without the metasurface, the proposed design provides more than ~4 dB higher gain both frequencies. It is clearly seen that the metasurface affects on the radiation patterns of the AFDA with two distinct functions at different operating frequencies. These are included on a flat lens at 1.65 GHz and spatial filter reflector at 2.57 GHz.

Measured radiation patterns of the AFDA alone and with metasurface in co- and cross-polarized on $xz$- and $yz$-planes are depicted in Figure 6. Corresponding radiation patterns and realized gain of the proposed antenna are carried out in the anechoic chamber located at Wireless Communication Research Group, King Mongkut’s university North Bangkok (KMUTNB). Their appearances were affirmed that the original radiation of the AFDA is changed from bidirectional to the unidirectional radiation pattern after adding the metasurface.

4. DISCUSSION

The theoretical and experiment results show that the distinct direction of the radiation patterns can be controlled for 20 mm separation distance. This feature is highlighted in Figures 5 and 6, where the radiation patterns of frequencies 1.65 GHz and 2.57 GHz are displayed in 3D and polar coordinate. In Figure 5,
the maximum gains of 4.32 dBi at 1.65 GHz in the forward direction and 3.91 dBi at 2.57 GHz in backward can be obtained, compared with the AFDA alone of 0 dBi. It means that the metasurface effectively increases the antenna gain both forward and backward directions. Remember that the metasurface is the reflective type, so the plane wave cannot pass in an ordinary case. To better understand the effect of separation distance on radiation patterns and front-to-back ratios (FBRs), the parametric analysis is performed as shown in Figures 7 and 8, respectively. Figure 7 shows the far-field radiation pattern in E-plane (xz-plane) with selected separation distances at \( \lambda_0/3, \lambda_0/5, \lambda_0/7, \lambda_0/9, \) and \( \lambda_0/13 \) for both frequencies of 1.65 GHz and 2.58 GHz. In Figure 7(a) at 1.65 GHz when \( d_a \) is reduced, the radiation patterns are the trend to forward direction whereas cases of 2.57 GHz are mostly reflected. Specifically, in cases of \( d_a = \lambda_0/7, \lambda_0/9, \) and \( \lambda_0/13 \) at 1.65 GHz, it can be observed an extraordinary transmission that these distances are the evanescent region and convert to propagation region. To summarize and compare, the corresponding dependencies of FBR as the function of the distance \( \lambda_0/N \) are presented in Figure 8. To clarify, this diagram is divided into three regions, each region representing two-frequency beam directions: (I) backward beams, (II) contrary beams, and (III) forward beams. All three regions are labeled. There are three boundary shade areas that separate beam directions from one another. In region I, in fact, the radiation patterns for both frequencies are confined in the backward half-space (below the metasurface) corresponding \( N \) between 2 and 4 whereas in region III the radiation patterns show in the forward half-space. The region I is similar the plane wave excitation due to the reflective type metasurface. Region II is limited to \( N \) between 5 and 7, the two beams are opposite directions which one at higher frequency is pointing the forward direction and the other is backward. Consequently, to develop the contrary beams, one needs to choose correctly the separate distance...
operate with contrary beams when 
d distracted, we can conclude that the separation distance 
the conversion of evanescent to propagation waves [12]. There-
Finally, the closest distance is in region III which this region is 
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\[ d_0 = \frac{\lambda_0}{N} \]

Properly speaking, the proposed antenna is able to 
operate with contrary beams when \( d_0 \) is between \( \frac{\lambda_0}{5} \) and \( \frac{\lambda_0}{7} \). Finally, the closest distance is in region III which this region is 
the conversion of evanescent to propagation waves [12]. There-
therefore, we can conclude that the separation distance \( d_0 \) is the key 
factor to determine its radiation characteristics.

5. CONCLUSION
The functions of the metasurface can be easily altered between 
transmission and reflection by simply changing the distance 
between the anisotropic fractal metasurface and the radiating 
element. The concept of the proposed antenna provides a unique 
opportunity to switch the direction of the main beam and to commu-
nicate at different operating frequencies. Moreover, the designed 
antenna presents a very low profile, since the whole antenna system 
thickness is of 0.17 \( \lambda_0 \) at the higher frequency band of operation. 
The proposed metasurface-based antenna configuration can be 
potentially adopted in modern smart communication systems.

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