Hash Unit Cell Shape Used To Enhancement Gain and Bandwidth of Metasurface Antenna

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Abstract

In this paper, Low-profile, high gain and wideband antenna loaded with a single layer metasurface are proposed. The process of adding the metasurface layer depends on the Fabry Pérot technology, which required existing an air gap among the slot antenna and the metasurface layer. The metasurface layer consists of an array of 4 x 4 unit elements placed on a Roger Ro4003C substrate layer with a thickness of 2.5mm. Hash shape is used as a radiating element. The metasurface MS is acting as left-hand material in which both permittivity and permeability are negative, leading to negative refractive indexing. The emitted waves from the slot antenna are affected by a set of unit cells on the metasurface MS above the slot antenna because of the structure's equivalent relative permeability and permittivity changes, and the slot antenna performance changes accordingly. The antenna works at a frequency of 6.75 GHz as a resonant frequency with an improvement in the bandwidth value for the metasurface antenna to get a value of 2.2 GHz instead of 390 MHz for the slot antenna. The proposed antenna has a 37 % bandwidth impedance starting at 4.7 GHz and ending at 6.9 GHz with a 7.43 dB gain value. The suggested antenna is useful for use with Wi-Fi applications.

1-Introduction

Recently, several modern technologies have emerged that have significantly led to the improvement in antenna efficiency in relation to the antenna gain and the expansion in bandwidth to reach both the Ultra wideband and the Multiband [1,2]. The advent of metasurface as a new and distinctive technology in the field of antennas, an artificial electromagnetic material that is not present in nature, has the potential to manipulate electromagnetic waves, to regulate the mechanism of electromagnetic waves' transmission and reception [3,4]. The metasurface is a two dimensional updated version of the oldest three-dimensional version called metamaterial . Metasurfaces are distinguished from metamaterial with many differences, such as ease of manufacture compared to the difficulty that encounter in a metamaterial, low structure and fewer losses [5,6]. In several applications, metasurface is used as an example of a set of significant applications, invisibility, absorber, imaging, direct emission of EM wave, quantum communication, beam shaping, reflective sheets, quarter-wave plates and direct emission of EM wave [7-9]. One of the most important parameters to be provided with metasurface layer design is the periodicity and thickness of the metasurface layer in order to classify the layer as a homogeneous surface and therefore to be considered metasurface[10,12]. The size of the cell unit is needed to be much smaller than the wavelength and the thickness, too. Permeability, permittivity
and hence the refractive index are the most important elements that are affected by this arrangement and how the layer is organized [13,14]. One of the most common types of antennas is the Microstrip antenna and the reason for this light in weight, low cost, simple feeding, analyses and easy to fabricate. Despite all these advantages, the microstrip antenna suffers from low gain and bandwidth, and surface wave excitation [15]. These obstacles affect the overall efficiency of the antenna. Researchers have found several methods that aim to increase the bandwidth, such as increasing the thickness of the substrate, with a low value of the dielectric constant [16]. Although, there is a restriction in antenna height that is necessary to be very small. The utilize of parasitic elements in the antenna results in doubling the resonance phenomenon that mostly alters the antenna's resonant frequency or introduced extra resonance frequency, resulting in a decreased bandwidth. By using a multi-layer substrate there is a decrease in the surface wave and at the same time there is raise in bandwidth to a good level but is offset by a decrease in the antenna efficiency and also it's gain. So, to raise bandwidth along with enhanced gain, there is a need for thick substrate or multi-layer substrate with low loss tangent, low permittivity that suppresses surface waves to increase bandwidth along with improved gain [17]. Therefore, the use of the metasurface technique that works to focus the radiation emitted from the conventional microstrip antenna in a narrow range, which leads to an increase in the antenna gain as well as the bandwidth width [18]. The combination of antenna gain and its bandwidth as well is what we are working on in the proposed antenna to be suitable for wireless application which is Wi-Fi.

In this paper, we present an antenna that depends on the Left-Hand material (LHM), which is the metasurface. The proposed antenna operates at a resonance frequency of 6.75 GHz for a frequency range from 4.7 GHz and to 6.9 GHz with a gain value estimated at 7.43 dB.

2-Antenna Design

The antenna is designed based on metasurface, with the hash shape of patches unit cells. The aim of using of such a periodic metasurface structure is to enhance some antenna performance parameters such as gain, bandwidth, and return loss (matching) as will be seen later, where the proposed antenna structures are divided into three parts, a microstrip transmission-line feeding, a slot antenna, and a metasurface layer. The energy provided by the microstrip feeding is coupled to the slot antenna where the slot antenna launches electromagnetic waves into space. The metasurface which in turn is electromagnetically coupled to the slot antenna focuses the launched waves in smaller areas. Thus, the antenna radiation beams become narrower and the gain becomes higher. Because the metasurface layers consist of 2D distributed hash metallic unit cells made from copper with a certain number of cells separated by a gap width of (G), the proposed antenna has a large number degree of freedom to improve its functionalities.

2.1-Slot antenna

Figure 1 displays the design layout of an proposed antenna, consisting of only a rectangular slot fed by the aperture coupling technique. The length of the slot X determines the resonant frequency, according to the half wavelength while the slot width Z plays a vital role in optimizing the antenna matching. a slot is etched on the top of the substrate and the microstrip transmission-line is printed on the bottom of the substrate. The substrate is RO4003C with thickness of Q1=2.5mm, loss tangent 0.0025, and dielectric constant ε=3.55. Table 1 presents the slot antenna dimensions, all dimensions in mm.
The feeding is 50Ω microstrip transmission line. As can be seen, it extends beyond the slot to reach the optimum matching. The distance beyond the slot should be around a quarter wavelength $\lambda/4$ at a frequency of interest to effectively excite the slot. Since the microstrip transmission-line is open-ended, the current reaches its maximum value at the slot. This procedure aids to transfer the energy from microstrip transmission-line to a slot. One of the conventional slot antenna disadvantages is its narrowband response, so using the metasurface assists to widen the bandwidth. Furthermore, there are a lot of ways to increase the bandwidth, but most of them do not enhance the gain. The most attractive property carried out by using the metasurface is the enhancement of the gain as given in the following subsection.

### 2.2 Metasurface with Hash Shape Unit cells

This research work is primarily concerned with the designing of small footprint antenna for wireless applications. To bear in mind, the proposed design can be scaled up or down to obtain any frequency, so the design is frequency scalable. In this part, a metasurface layer, consisting of periodic $4\times4$ metallic patches (Hash unit cells) with equal dimensions is added at the top of slot separated by a distance hair. The space between the slot and the metasurface layer is air. The metallic patches (Hash unit cells) are etched over an RO4003C substrate with thickness $Q=0.813$ mm, the loss tangent of 0.0025, and relative permittivity $\varepsilon = 3.55$. The gap between the unit cells is $G=2$ mm. Height of the air cavity is 1 mm. These dimensions are obtained after a huge number of simulations to realize the best responses for the proposed. Table 2 presents the dimensions of metasurfaces hash unit cell.
Figure 2: shown (a) Top view of metasurface (b) hash unit cell (c) Feed line and slot  (d) 3D view of proposed antenna

Table 2: Final antenna dimensions of hash unit cell

| No | Symbol | Value  |
|----|--------|--------|
| 2  | G      | 0.5 mm |
| 3  | A      | 2 mm   |
| 4  | B      | 2.1 mm |
| 5  | C      | 2.1 mm |
| 6  | D      | 1.05 mm|
| 7  | E      | 2.1 mm |
| 8  | F      | 2.1 mm |
| 04 | T      | 1.05 mm|
| 00 | N      | 2.1 mm |
| 01 | M      | 2.1 mm |
| 02 | S      | 23.5 mm|
| 03 | W      | 4.4 mm |
The metasurface is placed in the near-field region of the slot antenna. The waves have a spherical-like phase behavior, so adding the metasurface in front of the spherical waves converts them to plane waves, being in-phase as shown in figure 3. In other words, these periodic unit cells converge the electromagnetic waves in narrower volumetric space, leading to increase the antenna gain and radiating for long distances. Furthermore, unit cells also enhance the impedance bandwidth by adding more resonance effects to the antenna response.

![Figure 3: A metasurface engineered with discrete elements that provide spatial phase distribution that offset the sphere-like front of the wave into a planar one [19].](image)

3-Result and Discussion

3.1 Extracting Permeability, Permittivity and Refractive Index from S-parameter

In this part of the discussion of the results of the our design, we talk about the method of extracting the results through which we can make sure that the design that was simulated in the CST is a design that depends on the metasurface in its construction. The parameter retrieval mode utilizing the S-parameters is employed to computation a curve for complex permeability and permittivity of metasurface depend on its unit cell element. After isolating only one cell from the design, placing it appropriately on the substrate and feeding it with a pair of the waveguide ports and applying the appropriate boundary condition from an appropriate electric and magnetic field we get the results based on CST program. The results of method is shown in fig. 4 below for permeability, permittivity and refractive index.
3.2 Reflection Coefficient, Gain, Directivity, Current Distribution

Figure 5 offers a comparison between results of only slot antenna and the slot integrated with metasurface layer. It is evidently observed how much bandwidth and gain have been attained when adding the metasurface layer. The bandwidth ranges from 6.84 GHz to 7.23 GHz for only slot antenna. This narrowband behaviour is dramatically changed to very wideband about 2.18 GHz, extending from 4.71 GHz to 6.89 GHz once the metasurface layer is added above the slot antenna. As pointed out earlier, this procedure aids to enhance matching for more frequencies, making the antenna very wideband. The improvement in the antenna bandwidth makes it a potential candidate for be utilized in some commercial wireless applications. In the absence of the MS layer, the gain of the slot antenna is about 4.28 dB, while in the presence of the metasurface layer, it results in 7.43 dB as a new gain as shown in Fig. 6. The gain enhancement obtained by the proposed antenna was about 3.15 dB. Moreover, the proposed antenna possesses gain values greater than a slot antenna over all frequencies. Increasing a gain value by 3.18 dB is not an easy task especially when utilizing small footprint single antennas where antenna designers know that. To do the same job using conventional ways, more than one antenna should be closely placed, called an antenna array with many disadvantages such as big footprints, matching complicated circuits, feeding network re-equipment's, etc.
3.3 Parametric Study For Hash Unit Cell Metasurface

The proposed antennas are carefully designed, and their operating functionalities must be calculated accurately. The parametric study given here provides such a good example to understand the working mechanism of the proposed antenna and which dimensions parameters impact the design performance. The slot length, the distance separating between the slot and the metasurface layer, Feeding length and width are chosen for this study for the sake of simplicity. These important parameters are set as a variable in the CST software, whereas all other parameters are fixed in the design. These parameters, which have a deep impact on the coupling between metasurface and slot, additional to the appropriate power supply to the antenna, have been varied. Fig. 7 shows the simulated return loss S11 of the proposed antenna for various slot lengths with fixed slot width =0.2 mm. The is varied from 6 mm to 11 mm with a step of 1mm. All slot lengths have

Figure 5: S11 of (only slot , slot antenna+metasurface)

Figure 6: Gain of (only slot , slot antenna+metasurface)

Figure 7: The simulated return loss S11 of the proposed antenna with various slot length from 6mm to 11mm.
almost the same resonant frequency. equal to 8 mm is the best choice because it offers wider bandwidth, see Figure 7 with the red trace. Many reasons can be inferred from this result that the slot and the feeding line may interact effectively over all this frequency range. Also, when the slot length increases, surface current becomes denser along the slot, so the equivalent inductance becomes larger. The increase in the inductance cancels out the capacitance impact of the air gap separating between the slot and the metasurface layer.

Next, an influence of the parameter on the S11 is also depicted in Fig. 8. equal to 1 mm is chosen. The bandwidth deteriorates as the air gap increases because the capacitance impact of the metasurface layer, which cancels out the inductance of the slot. Fig. 9 illustrate the change in values of both the length of the feed line and width to obtain the best specifications for the transmission line by reaching the appropriate length for the upper part of the slot location in the antenna. After the parametric study, the return loss S11 and gain of the slot antenna with hash distribution metasurfaces are given in Fig. 10, when Ls = 8 mm and =1 mm. The 3D radiation patterns for gain and directivity are depicted in Fig. 11. Table 3 introduces some the antenna performance parameters. Table 4 compares the proposed an antenna with other recent designs.

Figure 8: The simulated return loss S11 of the proposed antenna with various air from 0.6 mm to 1.6 mm.
Figure 9: (a) Feed line length various from 21.5mm to 26.5mm (b) Feed line width various from 0.4mm to 0.8mm.

Figure 10: (a) S11 for slot antenna with metasurface (b) Gain of Metasurface antenna

Figure 11: 3D Pattern for (a) Gain (b) Directivity
The efficiency of the antenna reaches to an approximate value of 96 % depending on the equation that collects between directivity and gains to give the efficiency.

Table (3, 4) antenna performance parameters

| No | Parameter        | Slot antenna | Metasurface antenna |
|----|------------------|--------------|---------------------|
| 1  | Resonant Frequency | 7 GHz        | 6.75 GHz            |
| 2  | Bandwidth        | 390 MHz      | 2.18 GHz            |
| 3  | Return loss      | -12 dBi      | -33.4 dBi           |
| 4  | Gain             | 4.28 dBi     | 7.43 dBi            |

| No | Work | Resonant Frequency | Bandwidth | Bandwidth | Return loss | Gain |
|----|------|--------------------|-----------|-----------|-------------|-----|
| 5  | [20] | 2.3 GHz            | 2 – 2.63 GHz | 630 MHz   | -22 dBi     | 1 dBi |
| 6  | [59] | 7.6 GHz            | 7-9 GHz   | 2 GHz     | -32 dBi     | 5.53 dBi |
| 7  | work | 6.75 GHz           | GHz to 3.60 | 2.18 GHz  | -33.4 dBi  | 7.43 dBi |

Until we get more insight into the electromagnetic characteristics of the metasurface antenna, generating the current distributions for the antenna at resonant frequency as shown in figures below:

Figure 12: Current Distribution at 6.75GHz
The figure shows the polar metasurface plot with hash shape of the unit cell. Where the value for the main lobe is (6.93) dB in the X-Y view ($\theta = 90^\circ$), whereas the main lobe direction has value ($38^\circ$), and the last the angular width value is ($52.2^\circ$). While the value for the main lobe is (18.9) dB in the Y-Z view ($\varphi = 90$), whereas the main lobe direction has value =1°, and the last is the angular width is ($61.9^\circ$). Finally, the X-Z view ($\varphi = 0^\circ$), the main lobe value is (19.2) dB, whereas the main lobe direction is value =49°, and finally the angular width value is ($138.7^\circ$)

![Figure 13: Radiation pattern(a) X-Y view (b) Y-Z view(c) X-Z view](image)

**Conclusion**

In this paper, metasurface-based, low-profile, high gain and wide bandwidth antenna are proposed. The metasurface consists of a single-layer of 4*4 patch array (hash metasurface patches located symmetrically around the centre along the x-axis), is placed over the slot antenna fed by a microstrip transmission-line located beneath the slot antenna. The proposed antenna work at 6.75 GHz. The antenna can appropriately work in the frequency band of 4.7GHz through 6.9GHz with -10dB impedance bandwidth of 37%, which is wider than that of the previous antennas mentioned above. The peak gain obtained in our proposed antenna is 7.43 dBi.

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