

Design Low Profile and Wideband Antenna Based on Metasurface

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Abstract—In this article, high gain, low-profile and wide bandwidth antenna, loaded with a single metasurface (MS) layer is proposed. The metasurface layer is composed of two sizes of periodic patches distributed along two dimensions. The size of large unit is divided to small four parts, establishing an approach to operate with a wide range of frequencies. Therefore, the variations in the unit cell size assist to widen the proposed antenna bandwidth and matching enhancement as well. This metasurface layer is added above the slot antenna, separated by a distance (h_{air}). The parameter h_{air} plays a vital role in determining the overall performance. Although the whole antenna consists of two layers, it still has low profile of $0.115 \lambda_0$, where λ_0 is the wavelength at centre frequency of 6.2 GHz. The most important achievement in our proposed antenna that it has wideband characteristics for both gain and impedance bandwidth simultaneously. The impedance bandwidth value is 5.8% ranged from 6.15GHz to 6.52GHz for the slot antenna alone, while the slot antenna loaded with the metasurface layer has the value of 40% impedance bandwidth from 5.62GHz to 8.43GHz. The peak gain attained in this research is 5.6dB, while it becomes 8.78 when adding the metasurface layer to the slot antenna. The gain enhancement is more than 3dB, considered as a good starting point to build antennas having high gains with no need to use antenna arrays which require special attention in their designs. Simulation results are as expected and provide a good comparison for the slot antenna before and after adding the metasurface to demonstrate the performance enhancement. The software used in all simulations is computer simulation technology CST.

Keywords— Metamaterial (MTM); Metasurface (MS); Slot antenna ; Low profile; Wideband; High gain, Fabry- Péro (F-P)

I. INTRODUCTION

Metasurfaces (MSs), which are two-dimensional (2D) thin layers, consider as successor of metamaterials which are 3-dimensional structures. MSs are consisted of several unit cells arranged periodically along two dimensions, supported by a thin substrate. They ease the fabrication processes and reduce the losses introduced by their ancestors, metamaterials [1]. In the current decade, metasurfaces attract attention of a lot of researchers to address many problems confronted before with metamaterials, ranging from UHF band to terahertz applications. A plethora of promising applications such as flat lens, spatial filters, beam formers...etc find the metasurfaces good candidates to simply carry out these duties [1][2]. Therefore, MSs are considered as sub-domains within the metamaterials [3]. Furthermore, the space between unit cells should not be larger than a quarter wavelength to guarantee that electromagnetic waves see homogenous materials.

The fascinating attributes of MSs lead to use them in broad range of applications such as compact planar circuits, polarization converter and rotator. In [4] [6], authors have used a diagonal metallic line in each center of unit cell, degenerating the incident electrical fields into two orthogonal modes with 90-degree phase shift. This process ensures the conversion of linear polarization waves to circular polarization. As known, the process of circular polarization generation requires two exciting sources, but MSs ease the process by using one exciting source. Another application where the MSs are used as surface-wave attenuator are widely utilized either in antenna arrays to reduce mutual coupling or in single antennas to improve the efficiency [7][8].

In both scenarios, these types of MSs called Electromagnetic band-gap structures EBGs resolve big problems which are the surface waves, known since the emergence of the first printed antennas. MSs, in other scenario called high impedance surfaces HISs, act to provide zero phase shift like magnetic conductors. The gap between, for example, the patch radiators in micro strip antennas and grounds are hugely shrunk, leading to low profile structures [9]. HISs, in literature, are also known as mushroom-like structures, reactive impedance surfaces RISs, or artificial magnetic conductors AMC [10][11][12][13][14][15][16].

In this research scope, MSs are used to enhance the performance and conquer several drawbacks, confronted researchers when designing conventional antennas. To make the radiation pattern steerable, authors in [19], have reported a means where some active elements are integrated among unit cells, making their phase shifts dynamic. The variable phase shifts lead to change directions of radiation beams. 5G or bonyad designers find this technique very useful to use ideally an infinite number of small radiators (i.e., unit cells), able to shape the incoming waves as required without employing complicated circuits as in traditional phased arrays. In [20], the directivity has been enhanced by adding a metasurface layer above the antenna. To obtain linear to circular polarizer, low profile antenna, readers can refer to [17] and [18], respectively. Employing Huygens surfaces which are MSs to compensate phases deviations resulting from the out of phase radiations is reported in [21], whereas in [22], metalens based on the principles of optic transformation is introduced in compensate phases in plane-like radiations.

Applying MSs in a field of superstrates that have exceptional properties not available in standard ones is also explored, leading to obtain substrates not observed before. This exploration encourages a lot of researchers as in [23] to design an antenna with high gain, wideband, and low profile. Moreover, compact wideband directive metasurface CWMS, being a novel way to enhance the antenna directivity is presented in [24], where the excitation method used to feed the antenna is via two-unequal slots. MS arrangement in a periodic fashion, composed of rectangular loop-based unit cells is deployed as a step to direct wave to the desired direction.

A leaky wave antenna based on MSs is proposed in [25]. The energy leaves the proposed structure gradually, wherever energy accumulated in space is added in phase, resulting in a constructive radiation

pattern. Other works as in [26][27][28][29][30] are about using metasurfaces in antennas. Reference [26] suggests a structure consisting of frequent unit cells which are complementary split ring resonators CSRRs, being main radiators. There is no explicit antenna. The results obtained have showed that the proposed antenna has very wide bandwidth, starting from 5.64GHz to 5.8GHz with gain value of 5.8dB. Two interleaved hexagonal ring resonators based a single unit cell to create a meta surfaces layer is proposed in [27]. This makes the design complicated to some extent. Using double ring resonators has doubled the bandwidth more than 110% from 200MHz to 420MHz and the gain is increased to 7.88dB. Under the same reason explained above, authors in [28], introduces a meta surface layer having patch unit cells with different dimensions. The simulated results show a wide bandwidth from 4.2GHz to about 5.6GHz and gain values is equal to 8.2dB. placing the meta surface layer beneath the antenna is reported in [29]. This meta surface is contributed into the matching enhancement, resulting in wide bandwidth. The enhancement is more than 500% where the bandwidth is increased from 100MHz to 630MHz. In [30], meta material MTM which depends on a S-shaped unit cell in its structure has been proposed. This work considers one of works that introduces very wide bandwidth which is about 2GHz and average gain is equal to 5.53dB. the proposed antenna is linearly polarized slot antenna. Also, circular polarized meta surface antenna is proposed in [31]. The attained gain is about 7.1dB.

In our work, we propose a new design based on a bowtie-like slot antenna integrated with a meta surface layer fed by a micro strip transmission line, called a Fabry– Pérot FP structure. The whole structure can only support linear polarization waves. According to the best of authors' knowledge, our design introduces an antenna with really very wide band for the first time. It considers as a new contribution to the research field. The gain is also enhanced. Both increments in the bandwidth and gain can make our work distinct. The software used in all analysis is computer software technology CST.

Eventually, the paper is organized as follows: first, the slot antenna and meta surface are introduced in section I independently. Section II presents a detailed explanation about the adopted unit cell. In section III, the slot antenna integrated with the metasurface layer is given. All designs and simulations are clearly indicated. The last part, section IV, draws the conclusion.

II. ANTENNA DESIGN

This research mainly deals with the design of a small footprint antenna. To bear in mind, the proposed design size can be scaled up or down to operate at any desired frequency, making an adjustable structure. In this section, we will discuss parts of the proposed antenna in detail, starting with the slot antenna as shown in Figure 1a. The slot antenna is cut out from a conductor layer placed over a RO4003C substrate with a dielectric constant 3.55 and a thickness of 1.5mm. The slot has two slot triangles attached to ends of slots, aiming to widen the bandwidth and enhancing the matching. This slot is excited by a micro strip feeding line with 50ohm characteristics impedance. This line extends about a quarter-wavelength at the desired frequency to excite the slot with a maximum current. The shape of extended line is a triangle as well for the same reason, broadening the bandwidth. Figure 1b shows the metasurface layer used in the proposed structure. As can be seen, unit cells have two different sizes. Each four patches within the small size unit cells are equal to one size of the big unit cell.

The bigger unit cell has side length equal to $M_x=M_y=5.42\text{mm}$ and the smaller one equal to $B_x=B_y=2.68\text{mm}$, see Figure 1b. The air cavity, known as Fabry- Parot FP resonating cavity is optimized at 3mm to obtain the highest possible gain. The radiated power is focused in smaller beams, resulting in high gain structures. For more information, interested readers can refer to [32]. The side view and three-dimensional views of the proposed antenna are portrayed in Figures 1c and 1d, respectively. Table I lists the proposed antenna dimensions. The dimensions given in the table are chosen after a huge number of attempts to optimize the antenna work.

Table I: Final antenna dimensions

No	Parameters	Symbol	Value
1	The side length of big patch	M_x	5.42 mm
2	The side width of big patch	M_y	5.42 mm
3	The side length of small patch	B_x	2.68 mm
4	The side width of small patch	B_y	2.68 mm
5	Gap between cells	A	0.7 mm
6	Gap between cells	C	0.16 mm
7	Substrate length	Y	40 mm
8	Substrate width	X	40 mm
9	Length of feed line	R_y	26.5 mm
10	Width of feed line	R_x	0.9 mm
11	Slot length	D_x	12 mm
12	Slot width	D_y	0.5 mm
13	Air gap 1	hair	3 mm
14	Substrate of slot antenna	S	0.813mm
15	Substrate of metasurface	S_1	0.81mm

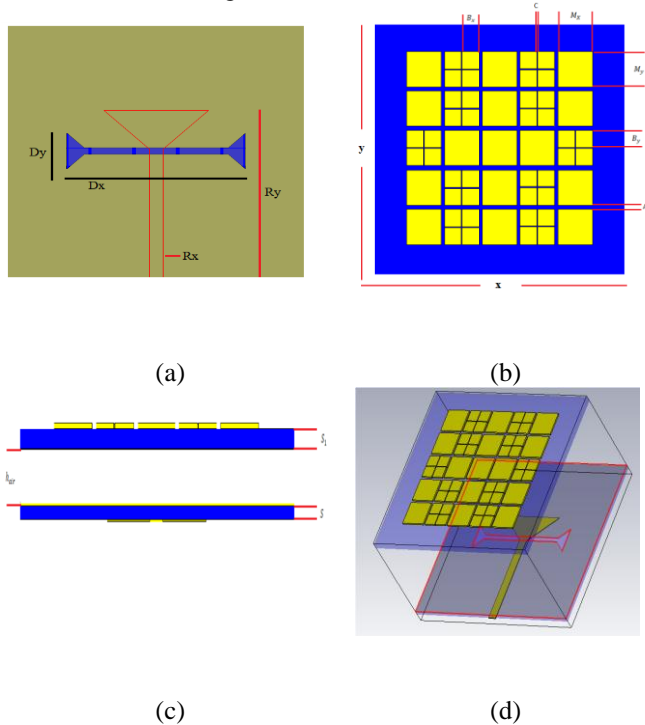


Figure.1: (a) Feed line and slot (b) Top view of metasurface (c) Side view of Antenna (d) 3D view of proposed Antenna

The variation in size results in a wide bandwidth. The distance separating between the slot antenna and the metasurface denoted by hair plays a vital role in determining the overall performance as will be seen later in this research study. Also, the RO4003C substrate is used to design the metasurface layer. The thickness S_1 is 0.81mm, the loss tangent is 0.0025, and the relative dielectric constant is 3.55.

The MS layer is added in the near field of the slot antenna, so the waves leaving the slot antenna that have spherical-like phase are converted to plane waves, being in phase. In other words, these periodic unit cells concentrate the EM waves in narrower volumetric space, leading to enhance an antenna gain and radiating for long distances. Furthermore, unit cells also improve an impedance bandwidth by adding many resonance effects into antenna response.

III. RESULTS AND DISCUSSION

Figure.2 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 6.15GHz to 6.52GHz for only slot antenna, being about 0.37GHz. This narrowband behaviour is dramatically changed to very wideband about

2.81GHz, extending from 5.62GHz to 8.43GHz once the metasurface layer is added above the slot antenna.

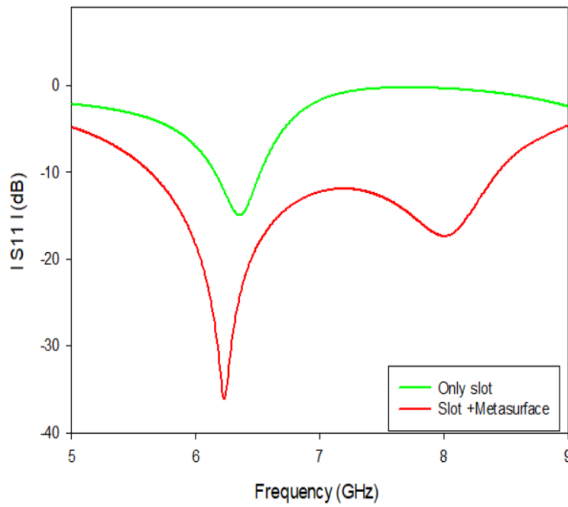


Fig.2 : Reflection coefficient S11

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 5.6dB, while in the presence of the metasurface layer, it results in 8.78dB as a new gain as shown in Figure 3. The gain enhancement obtained by the proposed antenna was about 3.18dB.

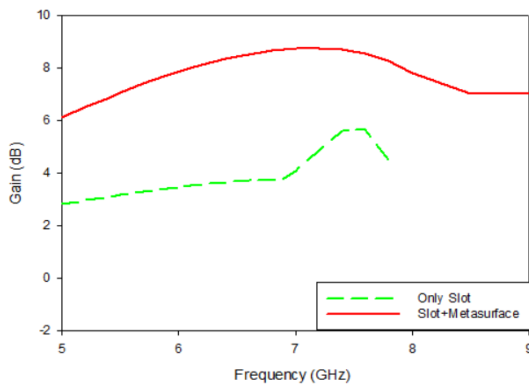


Fig.3 : Gain of slot antenna and metasurface

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.

Next, after showing the gain and the bandwidth of the proposed antennas, it becomes imperative to show impacts of the air gap separating between the slot antenna and the metasurface layer on the bandwidth and gain of the proposed antenna, after several steps of optimization. Figures 4 and 5 display the reflection coefficient S11 bandwidth and the antenna gain. As can be seen, when the air gap is equal to 3mm, the antenna offers the widest bandwidth compared to other distances. However, this air gap does not provide the highest gain, but it is acceptable if we consider the bandwidth trading off. The one thing that should be mentioned here as the air gap distance increases, the antenna bandwidth deteriorates, belonging to capacitance impacts of the cavity, created by the substrate hosting the slot antenna and the metasurface layer. See the results when the air gap is equal to 3.5mm and 4mm. As known the slot antenna has inductance characteristics, the capacitance provided by the cavity decreases for larger distances, thereby reducing the cancellation out of the slot antenna inductance. Thus, air gap with 3mm is chosen.

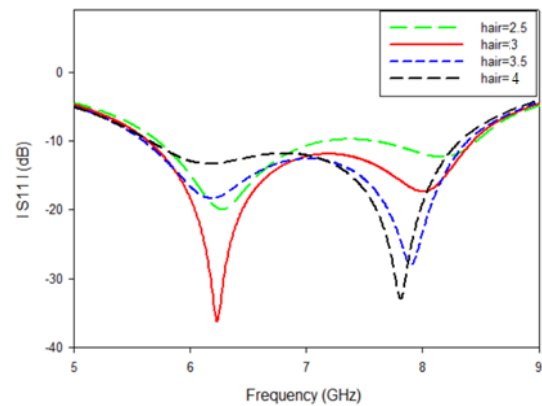


Fig.4 : Reflection coefficient S11

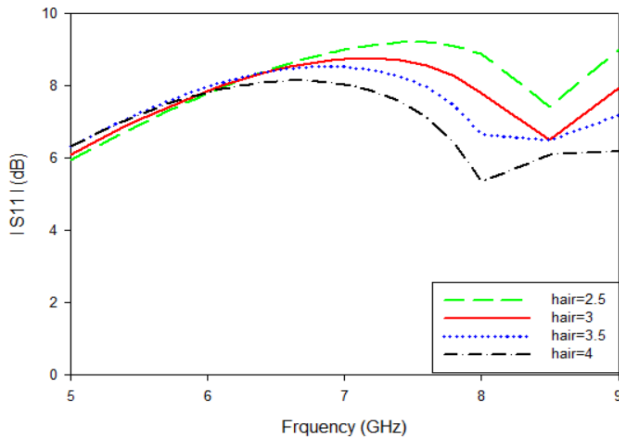


Fig.5 : Gain of proposed antenna

Table II introduces the results obtained for the slot antenna integrated with a metasurface layer, relying on the floquet theorem applied single unit cells of metasurfaces. This theorem provides whole information that the metasurface layer has negative permittivity, negative permeability, and negative refractive index using the S parameters algorithm. For more details, ref. [26] is the best option. The CST software was used in all analyses.

Table II : Proposed antenna result for (only slot antenna) and (slot antenna + metasurface layer)

No	Parameter name	Only slot antenna	Slot antenna + metasurface
1	Resonant Frequency	6.35 GHz	6.22 GHz
2	Bandwidth	6.15 GHz - 6.52 GHz	5.62 GHz - 8.43 GHz
3	Return loss	-14 dB	-36 dBi
4	Gain	5.6 dB	8.78 dBi
5	Directivity	7.88	8.94 dBi
6	Antenna efficiency	56%	98%

Table III is very important because it shows the strength of our contribution through the exceptional increase in the bandwidth, gain, and matching level compared to other related work. The value of impedance bandwidth is 40%, and this value can be obtained by applying Equation (2) in the reference [33]. This value is very excellent when compared to other reference, where work in [26] has value 2.7%, 7.4% for [27], 28% for [28], 27% for [29] and 25% for [30]. We also has increased the gain in the proposed antenna.

Table III : Comparing with other antennas

No	Work	Resonant Frequency	Bandwidth	Return loss	Gain	Directivity
1	[26]	5.7 GHz	5.64–5.8 GHz	-27 dBi	5.8 dBi	-
2	[27]	5.7 GHz	5.45-5.87 GHz	-17 dBi	7.88 dBi	-
3	[28]	5 GHz	4.20-5.59 GHz	-21 dBi	8.2 dBi	-
4	[29]	2.3 GHz	2 – 2.63 GHz	-22 dBi	1 dBi	-
5	[30]	7.6 GHz	7-9 GHz	-32 dBi	5.53 dBi	-
7	work	6.22 GHz	5.62-8.43 GHz	-36 dBi	8.78 dBi	8.94 dBi

IV. CONCLUSION

A proposed antenna with many advantages such as high gain, low-profile and wideband was introduced in this research work. The metasurface used here to enhance the performance was periodic metallic patches with two different sizes. The idea behind that is to have a metasurface with wideband frequency response. The air gap has been optimized and its best value has been chosen as 3mm. This value has been selected to trade-off between the gain and impedance bandwidth. The metasurface was able to remove all inductance impacts of the slot antenna, enlarging the bandwidth. Moreover, the metasurface was able to focus the energy in narrower beams, leading to enhancing the antenna gain. 5 x 5 unit cells are used in all metasurfaces in this research work, the height profile is about $0.115\lambda_0$ at the frequency of interest 6.22GHz. Furthermore, the impedance bandwidth value is 5.8% ranging from 6.15GHz to 6.52GHz for only slot antenna, while the slot antenna loaded with the metasurface has the value of 40% starting from 5.62GHz to 8.43GHz. The peak gain value is 5.6dB for only slot antenna and 8.78dB for the proposed antenna, slot antenna and metasurface layer, with gain enhancement about 3.18dB. Simulation results offer significantly improvement in the performance of the proposed antenna compared to the same without the metasurface layer.



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