Design of Low Profile and Wideband End-Fire Antenna Using Metasurface

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ABSTRACT In this paper, a metasurfing (MS) concept is demonstrated and applied in the design of the low profile and wideband endfire antenna on metallic surface environments. The MS comprises an array of varying patch printed on homogeneous host medium, and fed by a surface wave launcher (SWL). Each row patch is designed according to the operating wavelength and by altering the surface reactance of the MS the surface-wave mode can be manipulated into the free-space wave mode. Meanwhile, two row of rectangle patches with same size are located on between the surface wave launcher (SWL) and non-uniform MS, which is regarded as an impedance modulation to obtain a good impedance matching. The VSWR of the proposed antenna is below 2.5 from 3.8 GHz to 16.7 GHz in the measured results, which are in good agreement with the simulated results and the thickness of proposed antenna is only 5 mm (0.065λ\textsubscript{L}, λ\textsubscript{L} is the free-space wavelength at the lowest operating frequency). Moreover, a stable end-fire beam and low side lobe level (SLL) is obtained in a wide frequency band, and the group delay and the time-domain result also are shown to prove the good wideband transmission.

INDEX TERMS End-fire antenna, non-uniform metasurface, low profile, wideband antenna.

I. INTRODUCTION

In recent years, it is popular in the design of wideband flush-mounted endfire antenna owing to its wide applications in the aircraft, missile, and unmanned aerial vehicles. Many novel designs also have been proposed based on these metal platform [1]–[11]. However, comparing with the horizontally polarized endfire antenna [1], the vertically polarized endfire antenna has drawn extensive attention due to its integrating design with metal platform directly. In [2], a monopole Yagi antenna with a folded top-hat monopole as the driven element and four short-circuited top-hat monopoles as parasitic elements is studied, it achieves a fractional bandwidth of 20.5% and a low profile of only 0.033λ\textsubscript{L}. In [3], a log-periodic monopole array is designed on a large metallic plane by using top-hat loading of different sizes. It achieves a bandwidth of more than 3:1. Its further design based on three types of monopole configurations: conventional monopole, top-hat monopole, and folded top-hat monopole, is demonstrated in [4]. The antenna shows an extremely wide bandwidth from 2 to 18 GHz, and a low profile of 0.053λ\textsubscript{L}. On this basis, a capacitor-loaded hat is proposed to realize a very narrow transverse physical dimension [5]. Surface wave antenna is a good candidate to satisfy the requirements of low-profile, wideband and end-fire pattern. It has been demonstrated that a low profile of 0.065λ\textsubscript{L} and bandwidth of about 100% can be realized by employing a curved grounded ceramic slab [6], and the bandwidth can be enhanced by using non-uniform metasurface (MS) to suppress the TM higher-order mode [7]. H-plane horn antenna is another typical design to meet the requirements of low-profile, vertical polarization and wideband end-fire radiation, and is initially showed in [8]. To enhance the peak gain of the H-plane antenna, a dielectric lens with a linearly tapered profile is formed by elongating the supporting substrate beyond the aperture of the H-plane horn antenna [9]. Recently, slot antenna also drawn large attention in designing the endfire antenna mounted on a large metal platform, such as, a planar log-periodic cavity-backed slot

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array [10], microstrip-fed cavity-backed slot [11]. However, the longitudinal dimension among the antennas gradually is increased to obtain a broad bandwidth, which results in increasing the weight and the installation space.

On the other hand, the application of the uniplanar MS has attracted growing academic interest due to its simple manufacture process using standard printed-circuit techniques, low cost, low profile, and lightweight. One most prominent application of the MS proposed in the reported literatures is to enhance antenna performance, mainly including bandwidth enhancement or size reduction [12], directional improvement [13], polarization conversion [14], beam refraction [15], beam modulation [16], [17], filtering properties/functions [18]–[20], and so on. Especially, it also is known as impedance modulated surfaces, which are essentially leaky-wave antennas with radiation performance of high gain and arbitrary radiation beam.

Inspired by this, we propose a design of the low profile and wideband end-fire antenna using non-uniform MS, which can effectively reduce the longitudinal dimension of the antenna. The MS array is composed of two structures: two row of rectangle patches with same size, which improve the impedance transition, and fourteen rows of size-varied square patches. All patches are printed on a grounded slab, and fed by a surface wave launcher (SWL). With this structural arrangement, the antenna shows a low profile and wideband characteristic as well as a small longitudinal dimension. All simulated results are originated from the software ANSYS HFSS, and a prototype is fabricated and tested to verify the design.

II. ANTENNA CONFIGURATION

Fig. 1 shows the configuration of the proposed low profile and wideband end-fire antenna, which mainly consists of two parts: (1) a SWL operating in fundamental TE$_{10}$ mode, which is proposed in [7]; and (2) the MS array with a same height. Teflon substrate with a dielectric constant of 2.1 and loss tangent of 0.001 is used to design and implement the introduced surface wave launcher and MS array. A 50-$\Omega$ SMA connector is employed as the feeding source and the inner conductor of that is connected to the ridge of the surface wave launcher through a hollow metallic cylinder, whereas the outer conductor is directly soldered to the metallic ground plane.

In this design, fourteen rows of MS patches are used to transform the surface wave mode into free-space wave mode, and each row is denoted as a number $n$ ($n = 1, 2, 3, \ldots, 14$). The patch in each row has same size, but the size is varied according to the operating frequency along the end-fire direction. Suppose that the dimension of the $n$th row patch is indicated as $D_n \approx 0.11\lambda_n$, and the gap between the patches in each row is indicated as $d_n \approx 0.11D_n$. The space between adjacent rows is denoted as $w_n$. In order to improve the impedance matching, two rows of rectangle patches with same size are placed between the SWL and MS array. Its length and width are $l = 7$ mm and $w = 2.67$ mm, respectively. Moreover, the gap along $x$-direction and $y$-direction can be expressed as $s_1 = 0.5$ mm, and the spacing between SWL and the first row of patches is $s_2 = 0.2$ mm. It should be mentioned that to realize the antenna prototype the MS array is fabricated on a 0.508-mm-thick Rogers RO4003 substrate with a relative permittivity of 3.55, and then is embedded into Teflon slab seamlessly, as shown in Fig.1 (c). The combination slightly affects the MS size, but no effect of the bandwidth and radiation pattern, which can be included in the full-wave simulation.

III. ANTENNA ANALYSIS

A. ANALYSIS OF IMPEDANCE TRANSITION

It is seen from Fig.1 that the surface wave produced by the SWL propagates along the surface of the grounded dielectric slab. An impedance transition for matching improvement is produced between the SWL and non-uniform MS [21] owing to the small substrate thickness corresponding to the wavelength. For a comparison, three situations of the transition
are presented in Fig.2: 1) without the impedance transition, 2) loaded with two parallel plates between the SWL and non-uniform MS, 3) the parallel plate is divided into rectangle patch with same size and equal spacing along x-axis. The simulated impedance ($Z_{in}$) and voltage standing wave ratio (VSWR) curves for three situations also are illustrated in Fig. 3. It is observed that the VSWR without the impedance transition shows the poor impedance matching from 3.8 to 16.7 GHz due to the incident wave from the H-plane horn aperture is largely reflected. Thus, the energy not propagates forward effectively, which seriously reduces the excited efficiency of surface wave. In order to reduce the reflected wave as much as possible in the horn aperture, two row of parallel plates are employed in close to the horn aperture, which may be similar nature with magnetic director cells of Yagi antenna [22] to extend the radiation aperture so as to obtain matching improvement. The simulated VSWR loaded the parallel plate is less than the value without the impedance transition, and the change of resistance and reactance of the antenna trends to flat, which shows that the radiation field at the antenna aperture is optimized to increase the forward transmission of the antenna energy and reduce the backward reflection, so as to enhance the transition efficiency. In order to further improve matching, two rows of parallel plates are divided into rectangle patches along x-axis. The simulated VSWR also is shown in Fig. 3, which shows that the VSWR has been evidently improved compared with the antenna performance under the previous two situations.

B. DESIGN OF THE NON-UNIFORM MS

It is well known that when the thickness of dielectric slab reaches $h = \lambda/4\sqrt{\varepsilon_r}$, the surface impedance is smoothly decreased to radiation impedance, which implies that the surface wave is transformed into free space wave. Based on the lossless inhomogeneous metasurface reactance [23], the design procedures are summarized simply as follows:

1) In order to realize simple design, sub-wavelength square patch is used as the non-uniform MS array element. Each patch and the space between adjacent patches provide the needed surface impedance, and control the radiation performance. In our design, the patch dimension is selected to be about one-tenth wavelength based on the frequency requirement initially.

2) Based on the equivalent circuit model of the non-uniform MS array, the grid impedance of the MS and the surface impedance of the grounded dielectric slab can be obtained to determine the patch size $D_n$ and the space $d_n$ between adjacent patches in each row based on certain frequency initially [24].

3) Location and quantity of the non-uniform MS array can be determined. Based on the operating frequency, the first row and the last row patches, which are corresponding to the frequency of 4 GHz and 16 GHz, are determined. Then, smooth the dimension of the square
patch from 4 GHz to 16 GHz. Ultimately, all parameters are optimized by using HFSS. It is found that the fourteen rows of square patches are enough to produce a good gain pattern and large impedance bandwidth.

4) The spacing between impedance transition and the first row of the non-uniform MS should also be determined by using HFSS to obtain good performance.

It is noticed that in certain frequency every parameter has effect on the antenna performance, thus based on above design procedures the final antenna structure need be optimized by using HFSS systematically.

IV. EXPERIMENTAL VERIFICATION

A prototype of the proposed wideband endfire antenna is fabricated and measured, as shown in Fig.4. It should be noticed that a large ground plane is used in the design, though other values also are possible. The dimensions of the proposed antenna are presented in the Table 1. The VSWR of the proposed antenna is measured by using a calibrated Agilent vector network analyzer N5230A, and the radiation performance is measured in a microwave anechoic chamber. A Sub-Miniature 50 \( \Omega \) panel mount connector, which is operated from 0 to 24.5 GHz, is used in the measurement.

Fig.5 shows the VSWR results of the proposed antenna. It is seen that the measured VSWR is less than 2.5 over the frequency ranges of 3.8 GHz-16.7 GHz (125.8%), which is complied with the simulated results.
FIGURE 7. Simulated and measured peak gain, aperture efficiency, and simulated radiation efficiency results of the proposed antenna.

TABLE 1. Geometric dimension of the proposed antenna.

| Parameter | Value (mm) | Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|-----------|------------|
| W         | 146        | h1        | 4.2        | w4        | 0.8        |
| L         | 166.6      | D         | 2.6        | w5        | 0.85       |
| W-patch   | 66         | d         | 1.27       | w10       | 0.9        |
| L-patch   | 64         | Dp        | 0.1065p   | w11       | 0.95       |
| W-horn    | 25         | w1        | 0.3        | w12       | 1          |
| L-horn    | 46.6       | w2        | 0.5        | w13       | 1          |
| W-ridge   | 4.2        | w3        | 0.5        | w14       | 1          |
| L-ridge   | 45         | w4        | 0.6        | w         | 2.7        |
| d_post1   | 10         | w5        | 0.65       | l         | 7          |
| d_post2   | 63.3       | w6        | 0.7        | w         | 2.7        |
| d_feeding | 6          | w7        | 0.75       | W-caliber | 58.4       |

Fig. 6 plots the 2D far-field gain pattern of the proposed antenna in E-plane and H-plane at the frequencies of 6 GHz, 8 GHz, 10 GHz, 12 GHz, 14 GHz and 16 GHz. The simulated and measured radiation pattern approximately are in good agreement. It is shown from the figure that a good endfire pattern with a tilted angle of around 30° in E-plane is realized and an approximately symmetrical pattern also is observed in H-plane. Moreover, the cross-polarization level is at least 17 dB lower than the co-polarization level, especially in the end-fire direction.

Fig. 7 plots the simulated and measured peak gain curves versus frequency, which can be obtained by choosing the maximum gain of the E-plane pattern over the operating bandwidth. The simulated gain is 9.6 dBi at 4 GHz to 17.96 dBi at 15.5 GHz in the frequency of 4 GHz to 17 GHz, and the measurement gain varies from 8.6 dBi at 4 GHz to 16.67 dBi at 14.5 GHz. The simulated and measured results show that although the results decrease locally, they keep steady growth in the whole frequency band. It may be due to the tolerance in the manufacturing and installation error. In addition, the SMA connector as antenna feeding produces an insertion loss of about 0.2 dBi. The aperture efficiency and the radiation efficiency also are illustrated in Fig. 7. The aperture efficiency can be obtained by using the equation of $\varepsilon_A = \frac{\lambda^2 G_0}{(4\pi A_p)}$, where $G_0$ is the measured peak gain of the proposed antenna, $A_p$ is the physical size of the MS, $\lambda$ is the operating wavelength. The figure shows that the radiation efficiency is above 90%, and the aperture efficiency decreases as the frequency increases due to the decreasing the operating wavelength.

The group delay of the proposed antenna can be simulated using HFSS software and measured by placing two identical proposed antennas, one for transmitting (Tx) and
FIGURE 9. Normalized transmitting and receiving antenna signal waveform, (a) the proposed antenna, (b) the antenna in [25], (c) the antenna in [26].

were performed by using absorbing materials located on the space between the transmitting antenna and received antenna to eliminate multipath reflections from the ground plane. It is noticed that two identical antennas are connected to two measured ports of the vector network analyzer by two 50 Ω coaxial cable of about 3 meters and the output port of that can be calibrated by using standard calibration key. It is observed clearly from Fig.8 (b) that a discrepancy between simulated and measured results is noted, which may be attributed to the possible factors include the fabrication tolerance, scattering effect of tripod for supporting the antenna, and the alignment error of our measurement platform, as shown in Fig.8(a). The group delay is less than 2 ns in all frequency bands except 13 GHz-16 GHz, which indicates that the antenna exhibits linear transmission approximately.

The time domain impulse response of the proposed antenna in different direction of $\theta = 0$ (endfire-to-endfire), $\theta = 30^\circ$, and $\theta = 60^\circ$, which represents a tilting angle away from the end-fire direction, are investigated by using CST MWS software in Fig.9(a). It is seen that the output signal of the simulated receiving antenna has a large distortion comparing to the transmitting signal of the transmitting antenna when the two antenna is placed in $\theta = 0$ and $\theta = 60^\circ$ cases, whereas a little distortion can be observed when the antenna tilts away $\theta = 30^\circ$ from the endfire direction owing to different beam angles in different frequency, but the signal distortion is acceptable in the transmission of the wideband signals. This is because the main beams of the two antennas is directed in a straight line. It is shown the ringing effect is less in $\theta = 30^\circ$ case compared to the $\theta = 0$ and $\theta = 60^\circ$ case. In order to show the excellent transmission performance of the proposed antenna, the time-domain response of other good ultra-wideband (UWB) antennas also are shown in Fig.9 (b) and (c) for comparison. It is observed that in $\theta = 30^\circ$ case the time domain response of the proposed antenna indicates promising performance as well as the UWB conical monopole antenna [25], but better than that of the circular disc monopole antenna [26].

Table 2 shows the performance comparison between the proposed antenna and the other presented low-profile and wideband end-fire antenna in fractional bandwidth, profile size, peak gain, and the longitudinal dimension. It is observed that our proposed antenna has a smallest longitudinal dimension, while keeping a low profile, broad bandwidth, and high gain. The antennas in [4] and [5], based on folded top-hat monopole array, have large longitudinal dimension and small peak gain though its bandwidth is more than 160% and keeps low profile. Compared with the endfire surface wave antenna [7] which has a broad bandwidth, the proposed antenna shows higher peak gain and smaller longitudinal dimension. Compared with the H-plane endfire antenna [9], the proposed antenna has same antenna height, but longitudinal dimension more than two times less than that of the H-plane endfire antenna. The design in [10] has a smaller bandwidth and larger longitudinal dimension though it shows slightly lower profile than our antenna.
TABLE 2. Performance comparison between the proposed antenna and other vertically polarized endfire antennas.

| Reference | VSWR | Lowest operating frequency (λ₀ is referencing wavelength) | Fractional bandwidth (%) | Profile size (dBi) | Longitudinal dimension (mm) |
|-----------|------|-------------------------------------------------------------|--------------------------|-------------------|-----------------------------|
| [4]       | < 2  | 2 GHz (λ₀=150 mm)                                          | 160.6                    | 0.053λ₀          | 7.2-9.2                     |
|           |      |                                                             |                          |                   | 290 (1.93λ₀)                |
| [5]       | < 2.5| 1.19 GHz (λ₀=252.1 mm)                                     | 161.6                    | 0.063λ₀          | 4-7.5                       |
|           |      |                                                             |                          |                   | 520 (2.05λ₀)                |
| [7]       | < 2.5| 3.78 GHz (λ₀=79.4 mm)                                      | 132.3                    | 0.063λ₀          | 5.5-14.1                    |
|           |      |                                                             |                          |                   | 233 (2.93λ₀)                |
| [9]       | < 2.5| 2.5 GHz (λ₀=120 mm)                                        | 155.5                    | 0.066λ₀          | 3.61-18.7                   |
|           |      |                                                             |                          |                   | 314.09 (2.62λ₀)             |
| [10]      | < 2.2| 6.9 GHz (λ₀=43.5 mm)                                       | 86.4                     | 0.047λ₀          | 9.95-12                     |
|           |      |                                                             |                          |                   | 175 (4.02λ₀)                |
| This work |     | 3.8 GHz (λ₀=77 mm)                                         | 125.8                    | 0.065λ₀          | 8.6-16.67                   |
|           |      |                                                             |                          |                   | 116.5 (1.5λ₀)               |

V. CONCLUSION

In this paper, a low-profile and wideband end-fire antenna using an array of metallic patches as MS structure is proposed. The MS is composed of two structure: rectangle patch with same sizes and non-uniform square MS, where the rectangle patch is viewed as an impedance transition which can extend the horn aperture to obtain matching improvement. The design procedures of the array of square patches is discussed in this paper. The measured results show that the proposed antenna has a very wide bandwidth from 3.8 GHz TO 16.7 GHz with VSWR <2.5, and retains a low profile of only 0.065λ₀. Good gain and radiation pattern have been obtained within the operating bandwidth. The group delay and the time-domain performance in different rotation angles also are presented to show the promising performance as well as the two published UWB antennas.

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