Realization of Deep Tilt Angle, High Aperture Efficiency, and Low Sidelobe Using a Single Metaplate and a Patch Antenna

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ABSTRACT A beam-forming system for a patch antenna is proposed to realize a deeply tilted beam with high-gain, high aperture efficiency, and low sidelobe level. The proposed system uses only one novel metaplate, where the total system height is less than one wavelength. Firstly, a T-shaped metatwin is created as an element for the metaplate. It is revealed that the metatwin can provide a phase shift of more than 450° with change in the metatwin arm length. Based on this, secondly, a simulation is performed where a normally incident plane wave is refracted at a deep angle of 65° using a single metaplate. Thirdly, the incident plane wave is changed to a quasi-spherical wave using a small patch antenna. It is found that a 65° tilted beam is formed by virtue of a newly designed single metaplate. It is also found that a gain of 18.1 dBi is realized with an aperture efficiency of 49% and a maximum side lobe level of −14.6 dB. Fourthly, all simulated results, including the frequency response of the gain and S11, are validated using measured results.

INDEX TERMS Beam forming, deep tilt angle, metaplate, patch antenna.

I. INTRODUCTION

The radiation beams from patch antennas [1]–[3], loop antennas [4]–[6], and spiral antennas [7]–[10] are usually set to have their maximum intensities in the direction normal to the antenna plane (broadside direction), as shown in Fig. 1(a). For more effective communications, the antenna is often tilted, thereby directing the radiation beam toward a target, as shown in Fig. 1(b). Mounting such an antenna on, for example, a wall or a roof, causes the antenna to protrude into the air, resulting in a bulky, space-consuming arrangement.

However, the research in [11]–[17] has provided a solution for this antenna tilting issue, where a feed antenna is with \( N\) metatwin dielectric plates on which parasitic elements are printed. Such a dielectric plate is called a metaplate or metasurface. It has been found that a broadside radiation beam generated by the feed antenna is changed into a new beam whose maximum intensity is in the direction of the target specified by depression angle \( \theta = \theta_2 \) (the elevation angle is \( 90° - \theta_2 \)) by virtue of the metatwins, as shown in Fig. 1(c): up to \( \theta_2 \approx 50° \) for \( N = 2 \) [15] and up to \( \theta_2 \approx 60° \) for \( N = 3 \) [16]. Thus, if multiple metatwins are used, there is no need to tilt the antenna. It is inevitable that, as \( N \) is increased, the flatness of the beam-forming system is deteriorated. This causes a system height issue.

In addition to realizing system flatness, evaluation of aperture efficiency \( \eta_{\text{aperture}} \) is also important for, in particular, a system using flat plates (such as metatwins). Generally, as tilt angle \( \theta_2 \) becomes deeper, the gain is decreased with increase in the side lobe level, resulting in the reduction of \( \eta_{\text{aperture}} \). In fact, \( \eta_{\text{aperture}} = 40% \) in [14], 9.8% in [15], and 9% in [16]. In such a case, a physical antenna size must be larger to hold the required gain. This needs a larger space and raises an installation issue.

Then, questions arise as to whether a single metaplate \( (N = 1) \) can realize a tilted beam whose direction is close to or greater than the current deep value of \( \theta_2 = 60° \) [16], [19], [21] with low sidelobe level; and at the same time, whether this beam-forming system can exceed a current aperture efficiency of \( \eta_{\text{aperture}} = 40% \). If these questions are resolved with constructive results, the cost of design and fabrication will be drastically reduced, and the potential for application to modern communication systems is increased.
To confirm the validity of the simulation results, a low-profile patch-metaplate beam-forming system is fabricated and measured. The measured results for the radiation beam, S11, and gain of the beam-forming system are discussed in Section IV. Section V presents the conclusions, indicating that the antenna system meets all design requirements for $N_{\text{metaplate}}$, $\theta_2$, $\eta_{\text{aperture}}$, gain, MSL, and $H_{\text{total}}$.

Note that, in Table 3 of the Appendix, the proposed beam-forming system is compared with previous work [14]–[21] to reveal its novelty and usefulness. The previous systems are not found to meet all the challenging requirements specified in this paper. In [14], [17], [18], $\theta_2 > 60^\circ$ is not met, although $N_{\text{metaplate}} = 1$ is met. In [15], [16] and [19]–[21], the number of metaplates is $N_{\text{metaplate}} \geq 2$, which is against the main requirement of $N_{\text{metaplate}} = 1$, and the aperture efficiency is low, i.e., it does not reach $\eta_{\text{aperture}} > 40\%$, despite of $N_{\text{metaplate}} \geq 2$.

Also, note that the simulations throughout this paper are performed using an electromagnetic wave analysis solver based on a finite integration technique [22].

II. METATWIN

A. METASURFACE BEHAVIOR

To meet the required specification regarding the number of metaplates ($N_{\text{metaplate}} = 1$), a single dielectric substrate of relative permittivity $\varepsilon_r$ and thickness $B$ is used, where multiple pairs of T-shaped elements are printed on its top and bottom surfaces, as shown in Fig. 2: $2M + 1$ pairs in the x-direction and $2N + 1$ pairs in the y-direction, with neighboring distance $p$ (periodicity). The single pair of T-shaped elements on the top and bottom surfaces, which occupies a square area of side length $2L$ and a thickness/depth of $B$, is designated as the metatwin; it is specified by a central arm of length $L_c$, an x-directed arm length of $L_x$, and a y-directed arm length of $L_y$, where the width of all the arms is $w$.

The $(x, y)$ coordinates of the center point for each pair are expressed as $(pm, pn)$, where $m = 0, \pm 1, \pm 2, \ldots, \pm M$ and $n = 0, \pm 1, \pm 2, \ldots, \pm N$. Hereafter, the metatwin at $(pm, pn)$ is labelled as $mn$.

First, we investigate whether the metatwin has a transmission coefficient whose amplitude is unity, and a reflection coefficient that is extremely small. For this, we reveal the frequency response of the metatwin when a plane wave of an x-polarized electric field (parallel to the center arm of length $L_c$) impinges on it. Fig. 3(a) shows the calculated results regarding the normalized values of $Z_0 Y_{es}$ and $Z_{ms}/Z_0$ [23].

\[
Y_{es} Z_0 = \frac{2(1 - T - R)}{1 + T + R} \quad (1)
\]

\[
Z_{ms}/Z_0 = \frac{2(1 + T + R)}{1 - T - R} \quad (2)
\]

where $Z_0$ is the intrinsic impedance in free space; $Y_{es}$ and $Z_{ms}$ are the electric sheet admittance and magnetic sheet impedance of the metatwin, respectively; and $T$ and $R$ are the transmission and reflection coefficients (both complex), respectively. Arm lengths $(L_x, L_y) = (1.8 \text{ mm}, 3.8 \text{ mm})$.
FIGURE 2. T-shaped metatwin-based metaplate. (a) Perspective view of metaplate. (b) Top view of the metaplate. (c) Perspective view of a metatwin. (d) Top view of a metatwin. (e) Side view of a metatwin.

According to Eqs. (1) and (2), a Huygens surface [23]–[26] appears at a frequency where $Y_{es}Z_0$ and $Z_{ms}/Z_0$ are equal and purely imaginary. Such a case is observed at two frequencies, $f_1$ and $f_2$ , where the real parts are regarded as zero and the imaginary parts are nearly equal: $(Y_{es}Z_0, Z_{ms}/Z_0) = (0.04 - j1.897, 0.016 - j1.886)$ at $f_1 = 11.43$ GHz and $(Y_{es}Z_0, Z_{ms}/Z_0) = (0.005 - j1.827, 0.017 - j1.838)$ at $f_2 = 20.03$ GHz.

Fig. 3(b) shows the simulated scattering parameters, $|S21|$ and $|S11|$, for the metatwin. The results show that, at $f'_1$ and $f'_2$, the absolute value of the transmission coefficient is 0 dB (unity), with an extremely small reflection coefficient together with the parameters summarized in Table 1, are used to evaluate Eqs. (1) and (2).

TABLE 1. Parameters.

| Symbol | Value | Symbol | Value |
|--------|-------|--------|-------|
| $B$    | 3.2 mm | $\varepsilon_r$ | 2.6   |
| $p$    | 10.0 mm | $w$ | 0.4 mm |
| $L_c$  | 5.4 mm | $2L$ | 7.6 mm |
of less than −30 dB. Note that \( f_1' \) and \( f_2' \) are the same as the abovementioned equation-based frequencies \( f_1 \) and \( f_2 \): \( f_1' = f_1 \) and \( f_2' = f_2 \). It is also found that the metatwin has a wideband transmission characteristic across a frequency range from \( f_1 = 11.43 \) GHz to \( f_2 = 20.03 \) GHz (54.7%).

Fig. 4 shows the simulated current distribution along the T-shaped metatwin over one time period, \( T \), where the working frequency is \( f_1 = 11.43 \) GHz. The x-directed current on the top T-shaped element, \( \text{DoC}_{\text{top}} \), changes with a time step of \( T/4: +x, +x, -x, \) and \(-x\) directions; meanwhile, the x-directed current on the bottom T-shaped element, \( \text{DoC}_{\text{bottom}} \), changes as follows: \(+x, -x, -x, \) and \(+x\) directions. In other words, \( \text{DoC}_{\text{top}}, \text{DoC}_{\text{bottom}} \) at \( t = 0, (+, +) \) at \( t = T/4, (-, -) \) at \( t = T/2, \) and \((-+, +) \) at \( t = 3T/4 \). Note that a fictitious small magnetic current in the y-direction is generated at \( T/4 \) and \( 3T/4 \) by the two electric currents along an overlapping section of the top and bottom center arms. Also note that the y-directed currents on the top T-shaped element (red arrows) flow in the direction opposite to each other, and hence the y-directed electric fields (cross polarized fields) are canceled; the same happens for the y-directed fields generated by the currents on the bottom T-shaped element (blue arrows).

**B. EFFECTS OF METATWIN ARM LENGTH**

We further investigate the transmission coefficient \( S_{21} \) of the metatwin when the arm length is changed. Fig. 5(a) shows the simulated amplitude \( |S21| \) when the arm length \( L_L \) is increased from \( L_L = L_c \) through \( L_L = L_c + L \) to \( L_L = L_c + 3L \) within a square loop area of side length 2\( L = 7.6 \) mm. Note that the length \( L_L \) is illustrated in the inset of this figure. It is found that a good transmission characteristic is obtained from 10.8 GHz to 12.5 GHz for a criterion of \( |S_{21}| > -3 \) dB. It is also found that phase \( \angle S_{21} \) at 11.5 GHz shifts up to approximately 450° with change in length \( L_L \), as shown in Fig. 5(b). It follows that the metatwin has a phase shift of more than the 360° that is needed for beam formation.

**III. BEAM FORMATION**

**A. REFRACTION OF A PLANE WAVE**

For preparation of the design goal, a fundamental situation is considered here, where a plane wave (TE mode to the yz plane) impinges a metaplate from \( \theta_1 = 0° \) and is refracted in a direction of \( \theta_2 \), as shown in Fig. 6 [23]–[25].

For the refraction at \( \theta_2 \), phase \( \phi_{mn} \) is defined for the center point of metatwin \( mn \) as follows:

\[
\phi_{mn} = \phi_0 - mpk_{\text{DSN}} \sin \theta_2 \pm 2\pi v \quad (v = 0, \pm 1, \pm 2, \ldots)
\]  

(3)

where \( k_{\text{DSN}} \) is the wave number: \( k_{\text{DSN}} = 2\pi/\lambda_{\text{DSN}} \) with \( \lambda_{\text{DSN}} \) being the free-space wavelength at design frequency \( f_{\text{DSN}} \) (≈ 11.5 GHz). Eq. (3) means that neighboring metatwins have a phase relationship of \( \phi_{m(n+1)} - \phi_{mn} = -pk_{\text{DSN}} \sin \theta_2 \) in the x-direction and \( \phi_{m(n+1)} - \phi_{mn} = 0 \) in the y-direction.

Note that the required \( \phi_{mn} \) can be realized by selecting the appropriate L-shape length \( L_L \) from Fig. 5(b).

We evaluate Eq. (3) for a deep refraction angle of \( \theta_2 = 65° \) at frequency \( f_{\text{DSN}} \), where the number of metatwins is infinity: \( M = N = \infty \). For the simulation, a periodic boundary condition is used [22]. As seen from Fig. 7, the wave is refracted, as desired.

**B. TILTED BEAM FROM A PATCH ANTENNA**

Based on the validity of Eq. (3), we next consider a low-profile practical beam-forming antenna composed of a small patch antenna and a single metaplate \( (N_{\text{metaplate}} = 1) \), as shown in Fig. 8. The consideration is devoted to the realization of a deep tilt in the beam for \( \theta_2 \). Treating the patch antenna as a point source, Eq. (3) is changed into Eq. (4) using
As shown in Fig. 9, the patch antenna used here is square with a small side length of \( S_p = 7.0 \text{ mm} = 0.268 \) wavelength at design frequency \( f_{DSN} (= 11.5 \text{ GHz}) \). The dielectric substrate (of relative permittivity \( \varepsilon_{r-p} \) and thickness \( B_p \)) and ground plane supporting the patch are also square with side lengths \( S_{sub} \) and \( S_{GP} \), respectively. The small patch is fed by a 50-ohm coaxial line, where the feed point is shifted away from the center point by \( d_{FD} \) for impedance matching. The parameters are summarized in Table 2.

Fig. 10 shows the radiation pattern of the patch antenna at design frequency \( f_{DSN} \): the half-power beamwidth is \( \Theta_{HPBW/\text{xz}} \approx 99^\circ \) in the xz-plane and \( \Theta_{HPBW/\text{yz}} \approx 67^\circ \) in the yz-plane, and the gain is approximately 7.2 dBi in the z-direction. Note that \( E_\theta \) and \( E_\phi \) denote the \( \theta \)- and \( \phi \)-directed electric radiation field components, respectively.

We start with forming a broadside beam (\( \theta_2 = 0^\circ \)) at \( f_{DSN} \). L-shape length \( L_L \) is selected to obtain phase \( \phi_{mn} \) in Eq. (4), where \( 13 \times 13 \) metatwins are used (\( M = N = 6 \)).

\[ \phi_{mn} = \phi_0 - m \pi k_{DSN} \sin \theta_2 + (d_{mn} - h)k_{DSN} \pm 2\pi v \]  
\[ (v = 0, \pm 1, \pm 2, \ldots) \quad (4) \]

where \( d_{mn} \) is the distance from the point source located at \((x, y, z) = (0, 0, -h)\) to the center point of metatwin \( mn \):

\[ d_{mn} = [(pm)^2 + (pn)^2 + h^2]^{1/2}. \]

Eq. (4) means that neighboring metatwins have a phase relationship of \( \phi_{(m+1)n} - \phi_{mn} = (d_{(m+1)n} - d_{mn} - psin\theta_2)k_{DSN} \) in the x-direction and \( \phi_{m(n+1)} - \phi_{mn} = (d_{m(n+1)} - d_{mn})k_{DSN} \) in the y-direction.
Fig. 12(a) shows VOLUME 10, 2022 29

Second, \( \eta_{\text{eff}} \) efficiency of in the metaplate, as designed. In the following discussion, we use a distance of \( h = 0.75 \lambda_{\text{DSN}} \), leading to a total system height of \( H_{\text{total}} = B_p + h + B_{\text{sub}} = 23.57 \text{ mm} = 0.90 \lambda_{\text{DSN}} \), so that it meets the required total system height specification \((H_{\text{total}} < 1 \lambda_{\text{DSN}})\) described in the Introduction.

Next, we design a beam with a deep tilt of \( \theta_2 = 65^\circ \) in the xz-plane to meet the required specification of \( \theta_2 > 60^\circ \). Simulation is performed on the basis of Eq. (4) using Fig. 5 for L-shape length \( L_2 \). Such a deep tilt beam is formed based on near-field phase correction [27–33] for the metaplate. As shown in Fig. 5, the proposed metatwin realizes large transmission amplitude \((|S21| > -3 \text{ dB})\) with an arbitrary transmission phase \( \angle S21 \). This contributes to a high-gain beam when \( \angle S21 \) for metatwin \( mn \) is adjusted such that it generates in-phase radiation in a \( \theta_2 = 65^\circ \) direction. In other words, the radiation field is confined around the \( \theta_2 = 65^\circ \) direction. For better understanding of the high-gain, first, Fig. 12(a) shows \( \angle S21 \) for metatwin \( mn \) to form a 65°-tilted beam, when a plane wave impinges on the metatplate. Second, Fig. 12(b) shows \( \angle S21 \) given by Eq. (4), which takes into account the phase delay from a point source to metatwin \( mn \).

Fig. 13(a) illustrates the wave propagation behavior. The arrow shows a wave front direction of \( \theta_2 = 65^\circ \). Fig. 13(b) shows the simulated 2D and 3D radiation patterns, which confirm that a tilted beam is formed as designed. The gain in the \( \theta_2 = 65^\circ \) direction is 18.1 dBi, resulting in an aperture efficiency of \( \eta_{\text{aperture}} = 49.0\% \). The maximum side lobe is found to be MSL = −14.6 dB. Note that these simulation results meet the required specification values.

### IV. FABRICATION AND MEASUREMENT

The beam-forming system composed of the patch antenna and the metaplate in Section III is fabricated, as shown in Fig. 14, to confirm the deep beam tilt of \( \theta_2 = 65^\circ \). Fig. 15 shows the measurement setting in an anechoic chamber. The radiation pattern is measured by rotating the antenna system on the turntable, while a transmitting pyramidal horn antenna is fixed. The radiation pattern for the system, shown in Fig. 13(b), is measured at frequency \( f_{\text{DSN}} = 11.5 \text{ GHz} \) and illustrated by dots in the 2D pattern. For additional information, the measured radiation pattern for the isolated small patch antenna (i.e., the patch antenna without the metaplate) is added in Fig. 10. It is found that the measured and simulated results are in good agreement.

Fig. 16 shows the frequency response of the input characteristic in terms of S11. Note that S11 for the isolated small patch antenna is also presented for comparison. It is revealed that S11 with the metaplate and S11 without the metaplate have no remarkable difference. S11 of the patch together with the metaplate has a simulated bandwidth of 4.0% for...
FIGURE 12. Transmission phase on the metaplate to form a 65°-tilted beam, (a) when a plane wave impinging on the metaplate, and (b) when a spherical wave impinging on the metaplate, taking into account the phase delay.

FIGURE 13. Tilted beam at $f_{DSN} = 11.5\, \text{GHz}$. (a) Wave propagation behavior. (b) 2D and 3D radiation patterns.

FIGURE 14. Photo of the beam-forming system composed of a patch antenna and a metaplate.

FIGURE 15. Photo of the measurement setting.

FIGURE 16. $S11$ around design frequency $f_{DSN} = 11.5\, \text{GHz}$. a criterion of $S11 = -10\, \text{dB}$ (VSWR $\approx 2$) and 6.2% for a criterion of $S11 = -6\, \text{dB}$ (VSWR = 3). These bandwidths are acceptable for practical application.

The deviation of the tilted beam from $\theta_2 = 65^\circ$ and the gain in the direction of $\theta_2 = 65^\circ$ are shown as a function...
TABLE 3. Comparison of tilted beams. $\lambda_0$ is the wavelength at design frequency. $A$ is physical aperture.

| Tilt angle $\theta_2$ | Number of metaplates $N_{\text{metaplate}}$ | Aperture efficiency $\eta_{\text{aperture}} = G \lambda_0^2 / 4\pi A \cos \theta_2$ | Gain $G$ | Physical aperture $A$ | Maximum sidelobe level $\text{MSL}$ | Total height $H_{\text{total}}$ | Feed element | Polarization |
|----------------------|------------------------------------------|-------------------------------------------------|--------|-------------------|-----------------|----------------|-------------|-----------|
| Proposed $65^\circ$ (at 11.5 GHz) | 1 | $49.0\%$ | 18.1 dBi | $4.98\lambda_0 \times 4.98\lambda_0$ | $-14.6$ dB | $0.90\lambda_0$ | Patch | Linear |
| [14] $33^\circ$ (at 8.0 GHz) | 1 | $\approx 40\%$ | 17.4 dBi | $3.6\lambda_0 \times 3.6\lambda_0$ | $-12$ dB | $0.53\lambda_0$ | Patch | Linear |
| [17] $30^\circ$ (at 28.0 GHz) | 1 | $14.7\%$ | 15.8 dBi | $\pi \times 2.75\lambda_0 \times 2.75\lambda_0$ | $\approx -10$ dB | $0.95\lambda_0$ | Probe | Linear |
| [18] $34^\circ$ (at 30.0 GHz) | 1 | $2.5\%$ | 19.2 dBi | $17.5\lambda_0 \times 18.0\lambda_0$ | $< -10$ dB | $7.0\lambda_0$ | Slot | Linear |
| [15] $54^\circ$ (at 8.0 GHz) | 2 | $9.8\%$ | 17.3 dBi | $3.6\lambda_0 \times 3.6\lambda_0$ | $\approx -10$ dB | $0.77\lambda_0$ | Patch | Linear |
| [19] $60^\circ$ (at 7.0 GHz) | 2 | $33.8\%$ | 12.0 dBi | $2.73\lambda_0 \times 2.73\lambda_0$ | $\approx -8$ dB | $0.53\lambda_0$ | Patch | Linear |
| [20] $28^\circ$ (at 26.0 GHz) | 2 | $33.6\%$ | 21.5 dBi | $\pi \times 3.48\lambda_0 \times 3.48\lambda_0$ | $\approx -15$ dB | $2.87\lambda_0$ | Patch | Circular |
| [21] $60^\circ$ (at 13.5 GHz) | 2 | $12.8\%$ | 17.8 dBi | $8.64\lambda_0 \times 8.64\lambda_0$ | $-10.1$ dB | $7.0\lambda_0$ | Horn | Linear |
| [16] $\approx 60^\circ$ (at 8.0 GHz) | 3 | $\approx 9\%$ | $18$ dBi | $3.6\lambda_0 \times 3.6\lambda_0$ | $\approx -9$ dB | $1.01\lambda_0$ | Patch | Linear |

FIGURE 17. Frequency response of the beam direction.

FIGURE 18. Frequency response of the gain in a fixed direction of $65^\circ$.

V. CONCLUSION

It has been found that a patch-metaplate system can realize a radiation beam that meets the following characteristics: deep tilt angle of more than $60^\circ$, high gain of approximately $18$ dBi, and high radiation aperture efficiency of approximately $50\%$. These values have been realized under the two required conditions of the use of a single metaplate ($N_{\text{metaplate}} = 1$) and a small system height of less than one wavelength at the design frequency of $11.5$ GHz.

The design for the beam-forming system is performed in four steps. Firstly, a T-shaped metatwin is proposed and investigated. It is revealed that the metatwin has a wide frequency band of $14.6\%$ ($10.8$ GHz to $12.5$ GHz) for a $-3$ dB transmission coefficient criterion. It is also revealed that the
phase shift across this frequency region is extremely wide: 450°, which exceeds the 360° needed for beam forming. Secondly, a metaplate using T-shaped metatwins is designed to refract the wave front of a normally incident plane wave in a 65° direction. After the confirmation of the validity of this design, thirdly, the final metaplate is designed such that the quasi-spherical radiated wave from a small patch antenna forms a high gain beam in the 65° direction. The simulation for a system composed of the patch antenna and the designed metaplate shows that a 65° tilted beam is formed with a gain of 18.1 dBi, an aperture efficiency of 49%, and the maximum sidelobe level of −14.6 dB, where the total system height is small: 0.90λ.

Fourthly, the beam-forming system is fabricated, and measurements are performed. The measurements validate that the specified characteristics are all realized.

APPENDIX
See Table 3.

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