A High Efficiency Transmitarray Using Two-Layer Elements Etched on Compound Substrate

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ABSTRACT In this paper, a novel double-layer transmitarray antenna operating in X-band with high efficiency is presented. Different from the traditional transmitarray element design, the proposed transmitarray element uses a compound substrate which is composed of two horizontally arranged different dielectric substrate materials. By etching metal square loop and patch on both sides of the compound substrate, two resonance modes can be realized. Then, much enlarged transmission phase cover can be realized. The proposed element provides 360° transmission phase shifts with better than -2.3 dB transmission magnitudes, when the length \(L_2\) of the element varies from 5.95 mm to 9.05 mm. To experimentally validate this novel design, a 13 × 13-element transmitarray is designed, fabricated and tested. The measured peak gain of the transmitarray is 20.77 dBi at 10 GHz, with its aperture efficiency of 55%. This compound structure can also provide an additional degree of freedom in broadening the transmission phase shift range.

INDEX TERMS Double-layer, transmitarray antenna, high efficiency, low profile, lens antenna.

I. INTRODUCTION

The transmitarray is a new type of high-gain antenna, which has attracted more and more attention because of its superiorities such as low weight, low profile, high gain and without complex feed network. Generally, the transmitarray antenna (TA) consists of two parts: the illuminating feed antenna and the planar transmitarray with many transmitting elements. The feed antenna usually locates at the focal point of the planar transmitarray. Each transmitting element is individually designed to transmit the energy and to convert the spherical phase front from the feed to planar phase front. Then, the TA with high gain radiation characteristic can be realized.

Two most important design criteria for the transmitarray element are its transmission phase shift range and transmission amplitude. Generally, transmitarray elements with more than 360° transmission phases and higher transmission amplitudes are required. There are three different transmitarray design approaches to fulfill both transmission phases and amplitudes. One approach involves using multilayer frequency selective surface (M-FSS) [1]–[7]. As reported in [1], a four-identical-layer TA element using dual-resonant loop was presented, and this element can realize full 360° transmission phase range. In [2], a comparative analysis of different numbers of transmitarray layers was presented, and the proposed four-layer wideband element covers 360° transmission phase span. In order to further simplify the structure and improve the performance of TA, some three-identical-layer FSS structure elements were proposed, such as spiral dipole element [3], square slot with stubs element [4] and split diagonal cross element [5]. Moreover, different middle layer was used in three-layer transmitarray element design to achieve low-profile TA [6]–[8], and the coupling effect can be greatly improved by introducing the different middle layer. Actually, at least three layers of transmitarray structure were required to realize a full 360° transmission phase shift range, and the relationship between the number of transmitarray layers and the transmission coefficients were revealed in [9]. Recently, a novel double-layer TA elements was proposed to break through this limit. In [10], a double-layer transmitarray element using the element...
rotation approach was presented. Full $360^\circ$ transmission phase can be realized by rotating the circular polarization element.

The second approach of designing TA is to use receive/transmit structure [11]–[15]. By properly designing a coupling structure, the energy can be transformed from the receiving part to the transmitting part of TA. In [11], a planar TA combined with aperture coupling patch and stripline delay line was presented, and the proposed configuration provides preferable control of transmission coefficients. In [12], the concept of tightly coupled dipole was introduced in TA design, and the proposed TA presents ultra-wideband characteristic. Nowadays, some specially designed methods, including using metal via holes, were proposed to further improve the performance of the TAs. By loading via holes, the TA element realizes as much as $305^\circ$ transmission phase shift range, and the proposed double-layer transmitarray realizes 40% aperture efficiency [13]. In [14], two degrees of freedom element is used in a two layers 21 GHz TA design to realize 40% aperture efficiency. Furthermore, four metal vias and two cross-patches with two stubs are introduced in double-layer TA design, and higher aperture efficiency performance is realized in [15].

The third design approach is based on the technique of metamaterial transformation. The metamaterial-based TA element composed of periodic subwavelength structure with both magnetic response and electric response also has the capacity to manipulate the electromagnetic waves. Due to its unique property of controlling electromagnetic waves, a series of low-profile and high transmission TA were presented [16]–[19].

In this paper, a double-layer highly efficient transmitarray is presented. Different from the traditional transmitarray design, the proposed TA element uses a compound substrate. The substrate is made of two different dielectric materials arranged horizontally. By etching metal square loop and patch on both sides of the compound substrate, the phase shift range of the proposed element can be enlarged remarkably. Then, full $360^\circ$ transmission phase shift range can be achieved, and the maximum transmission magnitude loss is less than 2.3 dB. To validate this novel design, a $13 \times 13$-element transmitarray is designed, fabricated and tested. Measured gain of the transmitarray at 10 GHz is 20.77 dBi with 55% aperture efficiency. Table 1 also presents some previously reported transmitarray design. Compared with other existing work, this double-layer TA achieves relative high aperture efficiency without via holes. Moreover, this is a reference design with fewer layers. And this compound substrate technique also offers an additional degree of freedom to broaden the transmission phase shift range.

II. PROPOSED TWO-LAYER TRANSMITARRAY

A. ELEMENT CONFIGURATION

The proposed TA element has two metal layers, which are etched on the compound substrate. The compound substrate consists of two different dielectric materials, one is Arlon AD1000 (with 10.2 relative permittivity and 0.0027 loss tangent), and the other is Rogers 4003 (tm) (with 3.55 relative permittivity and 0.0027 loss tangent). The metal structure evolves from the top layer structure used for triple-layer TA [6]. The side length of the proposed element is chosen as $P = 9.6 \text{ mm}$ (0.32 wavelength at 10 GHz), and the thickness of the compound substrate is chosen as $H = 2 \text{ mm}$. The structure parameters of the TA element are illustrated in Fig. 1, and detailed parameter values of the proposed TA element are also presented in Table 2. ANSYS HFSS software is used to determine parameters of the element. Considering the coupling between the element and the surrounding unit cells, periodic boundary conditions and Floquet port excitations are used.

B. WORKING MECHANISM OF THE PROPOSED ELEMENT

The compound structure has two resonant modes: one is mainly from the square loop structure ($f_1$), and the other is from the patch structure ($f_2$). Fig. 2 presents the two
TABLE 2. Design parameter values.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $P$       | 9.6 mm | $W$       | $(P - L_2)/2$ |
| $G$       | 1.55 mm | $\varepsilon_1$ | 10.2 |
| $H$       | 2 mm   | $\varepsilon_2$ | 3.55 |
| $L_1$     | $L_2 - 2G$ | $L_2$ | vary |

FIGURE 2. Transmission response of double-layer TA element with single dielectric substrate and compound substrate. (a) Transmission magnitudes, and (b) transmission phases. (The incoming wave is $y$-polarized, and other parameters are $G = 1.55$ mm, $L_2 = 8.6$ mm, $H = 2$ mm, $L_1 = 5.5$ mm, $W = 0.5$ mm).

transmission peaks of the compound structure element. As can be seen from Fig. 2, the proposed compound structure introduces additional resonance in the frequency response, and it also increases the slope of the phase versus frequency curve from 7 to 12 GHz. Moreover, the physical mechanism of the two resonant modes can also be further understood by observing the current distribution. As shown in Fig. 3, the currents can be seen on the square loop structure for the first mode and on the patch structure for the second mode. By carrying out several times simulation experiments, we found that good transmission responses can be realized by using two dielectric materials with relatively large permittivity difference. Combining these two resonant modes properly will lead to larger transmission responses. Actually, only $y$-polarized wave can realize good transmission characteristics for this element design. The element performance will be analysed as follows.

FIGURE 3. Current distributions and electric field of the compound structure. (a) Current at $f_1 = 7$ GHz, and (b) current at $f_2 = 10$ GHz. (The incoming wave is $y$-polarized, and other parameters are $G = 1.55$ mm, $L_2 = 8.6$ mm, $H = 2$ mm, $L_1 = 5.5$ mm, $W = 0.5$ mm).

FIGURE 4. Transmission responses of the double-layer TA element versus $L_2$ at 10 GHz with (a) Different $G$ values, and (b) different $H$ values. ($L_1 = L_2 - 2G$, $W = (P - L_2)/2$, $\varepsilon_1 = 10.2$ and $\varepsilon_2 = 3.55$).

C. PERFORMANCE OF THE PROPOSED ELEMENT

Fig. 4 demonstrates the transmission responses of the proposed element versus $L_2$ value at 10 GHz with different parameters, $G$ and $H$ values. Here, the incoming wave is $y$-polarized, and only one parameter value is changed in each simulation experiments. As can be seen from Fig. 4 (a) and (b), the slope of the transmission phase curve increases.
FIGURE 5. Transmission responses of the double-layer TA element at 10 GHz with different oblique incidence angles. ($L_1 = L_2 - 2^* G$, $W = (P - L_2)/2, G = 1.55$ mm, $H = 2$ mm, $e_1 = 10.2$ and $e_2 = 3.55$).

greatly, when the length $L_2$ varies from 6 to 7 mm and from 8 to 9 mm, respectively. This is mainly due to the effect of two resonant modes. By optimizing the parameter of the TA element, we choose these parameters as $G = 1.55$ mm, $H = 2$ mm. The proposed double-layer TA element provides $360^\circ$ transmission phases with maximum transmission amplitude loss of less than 2.3 dB, when the length $L_2$ of the element varies from 5.95 to 9.05 mm. Furthermore, $310^\circ$ transmission phase range can be achieved with average transmission amplitude loss of less than 1.2 dB. Then, higher radiation efficiency transmitarray could be expected.

Generally, most of TA element are obliquely illuminated by the feed. So, the transmission responses of the proposed TA element under the oblique incidence waves are also analysed. Fig. 5 presents the transmission responses of y-polarized wave at 10 GHz. The parameters $\psi$ and $\theta$ are the azimuth and elevation angles, respectively, of the incidence wave. The transmission amplitudes become worse with the increase of incidence angles, especially for the incidence angles larger than 20 degrees. This is due to the blockage between the upper and lower layers. Different oblique incidence angles would cause blockage changes, which will affect the transmission coefficients. In order to ensure sufficient transmission coefficient, the oblique incidence angle of 20 degrees is chosen and the proposed transmitarray with a relative slight oblique incidence angle would be considered.

III. DESIGN AND VERIFICATION OF THE HIGH-EFFICIENCY TRANSMITARRAY

A. PROTOTYPE DESIGN

In order to validate the effectiveness of this novel double-layer element, two parts of the transmitarray, which are made of two different dielectric slabs and half of etched metal structure respectively, are designed and fabricated. These two different dielectric slabs are divided into thirteen segments, and the width of each segment is 4.8 mm (i.e. half of element periodicity). To ensure the stability of the electrical performance, every two half of metal structure is connected with 3M conductive fabric tape. Moreover, two adjacent dielectric substrates are fixed on the hollow cardboard with dielectric screws to ensure mechanical strength. The prototype of the double-layer transmitarray is shown in Fig. 6. The square transmitarray operates at 10 GHz and its side length is 124.8 mm. A linearly polarized pyramidal horn located 158.4 mm above the transmitarray aperture is chosen as the primary feed, and the aperture size of the feed antenna is 80 mm × 60 mm. The simulated gain of the feed antenna at 10 GHz is 17.3 dBi. The radiation patterns of the feed antenna can be considered equivalent to $\cos^{32}(\theta)$, and its $E$- and $H$-plane 10-dB beamwidths are 42.8° and 43.6°, respectively. The focal length ($F$) to the diameter ($D$) ratio is chosen as 1.27, which is a careful consideration of the available incidence angles. The required compensation phase of each unit cell can be calculated using the equation [1]:

$$\phi_j = k(R_j - F) + 2n\pi, \quad 0 < \phi_j < 360^\circ, \quad n = 0, 1, 2, \ldots .$$

(1)

where $R_j$ is the distance between the feed and the $j$th unit cell, $k$ is the propagation constant, $\phi_j$ is the required compensation phases of the $j$th unit cell, and $k$ is the propagation constant.
The designed TA elements phase distribution of the aperture is shown in Fig. 7.

B. EXPERIMENTAL VERIFICATION

The fabricated double-layer TA is tested in an anechoic chamber. To improve the measurement environment, a simple sliding transmitarray fixture is used to ensure the spatial position between the transmitarray aperture and the feed antenna. The simulated and measured radiation patterns of the double-layer TA at 9.55 GHz, 10 GHz and 10.3 GHz are presented in Fig. 8. As shown in the figure, the measured main lobe and first side lobe keep consistent with the simulated ones. The measured first side lobe and cross-polarization levels at 10 GHz are −14.1 and −36.5 dB, respectively, which present slightly different from the simulation results. The measured and simulated gains within the frequency band of interest are also shown in Fig. 9. The measured and simulated gains at 10 GHz are 20.77 and 21.29 dBi, respectively. The measured aperture efficiency is a little worse than the simulated one, which are 55% and 61.9%, respectively. The aperture efficiency (η) can be calculated using the equation [13]:

$$\eta = \frac{G}{D_0}, \quad D_0 = \frac{4\pi A_e}{\lambda_0^2}$$ \hspace{1cm} (2)

where $D_0$ and $G$ are the maximum directivity and measured gain, respectively, $\lambda_0$ stands for the free space wavelength, and $A_e$ is the physical dimension of the aperture. The proposed double-layer transmitarray shows a relative high aperture efficiency without using via holes. The relative high aperture efficiency is mainly due to the appropriate spillover and taper losses (0.5 and 0.4 dB), element transmission loss (1.25 dB). The gain discrepancy between measurement and simulation results are mainly due to PCB fabrication errors, antenna setting errors and measurement errors (0.5 dB). The measured 1-dB gain bandwidth is 7.5% (9.55-10.30 GHz), which presents a good bandwidth performance. The author also simulates a larger transmitarray prototype of $19 \times 19$-element ($6.08 \times 6.08$). The simulated gain at 10 GHz is 24.34 dB with aperture efficiency of 58.5%. The experimental results prove that the designed double-layer TA has higher aperture efficiency and wider gain bandwidth. However, compared with existing fabrication techniques, this fabrication scheme presented in this paper has disadvantages such as assembly difficulty, fabrication cost and inaccuracy. These can be improved by using 3D printing technology in the future.

IV. CONCLUSION

This paper uses a new design method to realize a high efficiency double-layer transmitarray. The proposed element only has two metal layers etched on the compound substrate.
By etching metal square loop and patch on both sides of the compound substrate, the 360° transmission phases can be realized, and the maximum amplitude loss is less than 2.3 dB. To validate this novel design, a prototype of 169-element transmitarray is designed, fabricated and tested. The measured peak gain is 20.77 dBi at 10 GHz with aperture efficiency of 55%, and the 1-dB gain bandwidth is 7.5% (9.55-10.30 GHz). Compared with other existing work, this compound double-layer TA presents relative high aperture efficiency and moderate gain bandwidth. Although, it is difficult to fabricate using standard PCB fabrication techniques, emerging 3D printing techniques may be used to overcome this limitation in the future.

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