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One-Dimensional Beam Scanning Transmittarray Lens Antenna Fed by Microstrip Linear Array

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ABSTRACT This paper proposed a one-dimensional beam scanning transmittarray lens antenna fed by a microstrip linear array antenna which owns a wide pattern in the plane orthogonal to the array axis and a narrow pattern in the plane that includes the array axis. The design principle of transmittarray lens aims to modulate a fan beam into a pencil beam by compensating phase shift of the linear array on the plane orthogonal to the array axis at X band. First, the Rotman lens feed network is used to implement nearly ±40° one-dimensional beam scanning for the linear array with 1 × 8 microstrip antenna elements. Then, a low-profile transmitted element with only one-layer of the substrate is utilized to design the new transmittarray lens, which can reduce fabrication expense and difficulties. After adding the transmittarray lens, maximum gain increments of 7.81 and 7.65 dB in simulation and measurement can be obtained in quasi-boresight directions, and gain increment could be obtained within ±25° beam scanning range. Besides, the fan beams of the original linear array are smoothly transformed into pencil beams.

INDEX TERMS Beam scanning, gain increment, Rotman lens, transmittarray lens.

I. INTRODUCTION Long distance wireless communications such as satellite, radar and deep space exploration cannot work without high gain antennas. How to increase antennas’ gain is still a hot topic so far. Traditionally, antenna elements are arranged in large-scale planar array for obtaining high gain. However, planar array antennas suffer from complex feed networks and expensive T/R modules. Under this circumstance, phase modulated surfaces come into being whose most common forms are reflectarray [1], [2] and transmittarray antennas [3]. Both of them are easy fabricated and low-cost since it benefits from PCB process. Reflectarray and transmittarray are widely used as high gain antennas by modulating phase distribution of the wave front into desired high gain beams.

Compared to reflectarrays, transmittarrays allows reducing feed blockage effect and offers more flexibility to modulate the phase of transmitted wave. Generally, a transmittarray lens antenna consists of a feed antenna as the illuminating source and a planar multi-layered structure. Each element on the transmittarray lens comprises a fixed transmission phase shift which is equal to phase compensation of path delay for feeding source and generation for a focused main beam at a desired direction. Common transmittarrays are transformation of multi-layer frequency selective surfaces which could cover wide range of transmitted phase shift [4], [5]. Another type of transmittarray can be classified as transmitter-receiver form [6]–[8] which employs transmission line structure for obtaining accurate phase shift easily. Both types of transmittarray are composed of at least three layers of PCB which greatly increase the profile and computing resource when designing the high gain transmittarray antenna. Whereafter, double-layer structure with vias is proposed at K band to design efficient and wideband transmittarray antenna which employs only one tier of substrate and two-layer of metallic patches [9], [10], greatly lower the profile and fabrication expense compared with multi-layer transmittarray.

Generally, transmittarray lens is based on variable-size principle which can only be used to generate fixed high-gain beams. Hence, electronically reconfigurable transmittarrays [11]–[13] come into being which can be used for generating electronically scanning high gain beams. PIN diodes or varactors are introduced in transmitted element design whose transmitted phase shift can be controlled by adding different bias voltages across the diodes. Reconfigurable transmittarray antennas are an efficient and low-cost...
way to generate electronically scanning beams, however, its structure and the control circuit of bias voltage for diodes is too complex to design. On the other hand, transmitarray lens is usually fed by a single antenna which include horn antenna, open-ended rectangular waveguide probe [14], patch antenna or substrate integrated waveguide (SIW) slot antenna [15] and so on. Transmitarray lens fed by a single antenna is inexpensive and with easy accessibility since no complex feed networks are required. However, they could not satisfy the demand for high-power field application such as high-power radar, impulse radar and guided missiles, et. al. This is because feed source with single channel can only transmit limited power into the space. Under this circumstance, inspiration of a trade-off scheme becomes increasingly clear which is combination of a linear array antenna and a planar transmitarray for generation of high-gain pencil beams. It can achieve high-gain pencil beam with higher transmitted power compared to single antenna fed transmitarray lens system.

It’s important to design an efficient feed network for a linear array antenna. Due to the high cost of transmit/receive modules (T/R module), linear array antennas are often fed by beam-forming networks, such as Blass matrix [16], Nolen matrix [17], Butler matrix [18] and Rotman lens [19]. The first three beam-forming networks require lots of couplers and phase shifters, leading to complex structure and large insertion losses. By contrast, Rotman lens is an attractive way to feed line array antenna which adopts geometrical optics approach defining a lens with three perfect focal points and excellent scanning performance over a wide angular range of ±35 degrees. Rotman lens has many advantages, such as wide operating bandwidth, simple structure, and easy fabricating. Rotman lens can be implemented for several realizations, such as microstrip [20], waveguide [21] and substrate integrated waveguide [22]. With true time delay and low cost features, Rotman lens has been widely used in multi-beam applications like inter-satellite link, satellite communications, automotive anti-collision radar and so forth.

In this paper, a design procedure for one-dimensional beam scanning transmitarray lens antenna fed by microstrip linear array is presented. The major feature of the design is that the transmitarray lens can modulate a fan beam to a pencil beam with a linear array antenna fed by Rotman lens. Section II presents the operating principle of one-dimensional phase modulated transmitarray lens for broadside linear array. Section III investigates the Rotman lens fed network for the linear array antenna which indicates that the Rotman lens can realize nearly ±40° one-dimensional multi-beam for linear array with 1 x 8 microstrip antenna elements. Section IV presents the design of low profile transmitted element with one-layer of substratem, performing good stability of polarization and oblique incidence. Then section V shows simulation and measurement results which both present that about 7.81dB and 7.65dB gain improvement could be realized in quasi-boresight directions by adding the proposed transmitarray onto broadside linear array, and gain increment could be obtained within ±25° beam scanning range.

II. DESIGN PRINCIPLES OF TRANSMITARRAY

Considering that a transmitarray is placed above a linear array antenna and Fig.1 presents configuration of the transmitarray for linear array antenna. Firstly, origin of the global coordinate system is set at O, and O’ represents the relative original point of transmitarray. The linear array antenna is oriented with each element centers at x = nd, n represents the sequence number, d is the element spacing and the elements are usually spaced one-half wavelength (λ0/2) apart (λ0 is the wavelength in free-space at frequency f0). According to phased array synthesis theory [23], the normalized array radiation pattern for a linear array with N-elements in the far field is calculated by the summation over all N-elements at frequency f0. Furthermore, in order to realize phase scanning in one dimension (maximum directivities are all in the direction of ϕ0 =0), each element in the linear array with all equal excitations owns phase shift of Pn = nk0d, and array factor could be presented as:

\[ F(u) = \sin\left[\frac{N \pi d_x (u - u_0)}{\lambda_0}\right] / \left[\frac{N \sin(\pi d_x (u - u_0) / \lambda_0)}{\lambda_0}\right] \]

where \( u = \sin(\theta)\cos(\phi) \), \( u_0 = \sin(\theta_0)\cos(\phi_0) \), \( k_0 = 2\pi/\lambda_0 \), and maximum directivity is realized in the direction of \( (\theta_0, 0^\circ) \). From equation (1) we can see that the broadside linear array in Fig.1 has a wide pattern in YOZ plane and a narrow pattern in XOZ plane where one-dimensional beam scanning can be realized by assigning phase shift of \( P_n = nk_0d, u_0 \)
to each element. Since the radiation pattern of a linear array antenna in the YOZ plane is still a wide beam, maintaining the original pattern of antenna element itself, transmitarray lens could be introduced to form high-gain narrow pattern in the dimension of $\phi_0$. That is, transmitarray only performs one-dimensional phase modulation in YOZ plane, as shown in Fig.1. Red shadows in Fig.1 indicate the interested reference YOZ plane, $r_i$ is position vector of the linear array which can also be expressed as $OO'$. $r_m$ represents $m$th transmitted element in the transmitarray along $Y$-axis and $r_0 = -r_i - r_m$. In the YOZ plane, the linear array could be modeled as a single antenna element at the origin of global coordinate system $O$, and transmitarray is placed above this antenna element model with one-dimensional phase compensation in $Y$-axis. Consequently, the phase shift on each transmitted element sheltered from red shadow can be written as:

$$P_m = mk_0 dsin(\theta'_0) - k_0 |r_0|$$  \hspace{1cm} (2)

where $d$ is spacing between every two transmitted unit cells along axis of $Y$ which depends on the period size of the unit cell. The expression of $k_0r_0$ in equation (2) indicates the path delay of the antenna element model and $mk_0dsin\theta'_0$ signifies the required phase compensation for a focused main beam at the direction of $\theta'_0$. Then the corresponding transmitted elements under red shadow are arranged in a column, and these columns of unit cells are duplicated to both sides of $X$-axis to form one-dimensional phase modulated transmitarray lens. It can be observed that the proposed one-dimensional phase modulated transmitarray lens along $X$-axis is uniform which nearly makes no difference to phase compensation for the linear array.

From the analysis above, it can be concluded that the operating principle of one-dimensional phase modulated transmitarray lens for broadside linear array can realize two-dimensional beam scanning which is essentially same as the performance of a planar phased array. Firstly, broadside linear array is designed to generate a main beam in the direction of $(\theta_0, 0')$; then transmitarray lens is designed to steer the existing beam along $YZ$ tangent plane with orientation of $\theta'_0'$. As a consequence, direction of maximum main beam $(\theta_0, \phi_0)$ can be expressed as follows:

$$\phi_0 = \arcsin\left(\frac{\tan \theta'_0}{\tan \theta_0'}\right)$$  \hspace{1cm} (3)

III. ROTMANN LENS FED NETWORK FOR LINEAR ARRAY

To achieve beam scanning performance for a linear array in practice, appropriate phase shift for each element is required. As is well-known, Rotman lenses are an attractive method to feed line array sources and they enable one-dimensional beam scanning with low phase-aberrations over a wide scanning angular range. It is designed based on geometrical optics approach (GO), and a typical configuration of Rotman lens is presented in Fig.2 (a) from which we can see that the inner-lens contour is connected to the input ports with transmission lines, also linking outer-lens contours to the linear array elements. And the contours of the inner and outer lens are defined in detail by a set of equations [19]. The focal arc was usually a portion of a circle passing through the three focal points. And other canonical focal curves have also been investigated, including elliptical [24] and hyperbolic [25] curves.

Here partial circle is selected to form the focal arc curve, as presented in Fig.2. By properly defining design parameters of these three contours, three distinct focal points are obtained: $G$, $F_1$ and $F_2$. In this paper, a combination of dummy ports in the vicinity of input ports and absorbers in the fringe of Rotman lens structure are utilized to absorb the reflection and diffraction of electromagnetic waves. On one hand, this Rotman lens structure could reduce the number of required matched loads; and on the other hand, it offers convenience for fabrication since it is easy to glue the absorbing materials onto the fabricated PCB board. The main dimensions of Rotman lens in Fig.2 are as follows: $A = 190$mm, $B = 217$mm and the gap between each output port equals 15mm.

The transmission lines in Rotman lens are designed by meandering lines whose bending parts are arc structures for smoothing transmission. For eight output ports along the outer-lens contour of Rotman lens, the transmission lines are designed with equal length to guarantee the phase shift for each antenna element is precise and stable. Fig.3 (a)-(d) presents phase shifts from each input port of Rotman lens to every output port in the frequency range from 9.4GHz to 10.4GHz. Since the Rotman lens is bilateral symmetry, phase shifts obtained by exciting input ports from 1 to 4 are provided here. From Fig.3 we can see that the output phase shift owns good linearity with low phase-aberrations from 9.4GHz to 10.4GHz. In addition, the return losses for each input port and output port of Rotman lens are depicted.
in Fig.4 below. It can be seen that the impedance matching for every port on Rotman lens is excellent. The insertion losses between input ports and output ports at 10GHz are given in Fig.5 from which we can see that the insertion losses are in the range from $-10\,\text{dB}$ to $-18\,\text{dB}$. Additionally, calculated insertion losses from each input port to all of the output ports are given in Fig.6. The average insertion loss of $3.2\,\text{dB}$ and $4\,\text{dB}$ can be obtained in simulation and measurement respectively from which it can be seen that Rotman lens feed network owns good performance and is qualified for feeding linear array antenna.

Then the assembly of broadside linear microstrip array antenna fed with Rotman lens shown in Fig.7 is simulated using numerical computation method. And the realized maximum gains under every input feed port of Rotman lens are $8.77\,\text{dBi}$, $9.54\,\text{dBi}$, $10.3\,\text{dBi}$, $10.6\,\text{dBi}$, $10.3\,\text{dBi}$, $9.54\,\text{dBi}$ and $8.77\,\text{dBi}$, respectively. Besides, steering angles of the main beam at each feeding port of Rotman lens are $-38^\circ$, $-26^\circ$, $-13^\circ$, $-0^\circ$, $13^\circ$, $26^\circ$ and $38^\circ$, respectively.

### IV. DESIGN OF TRANSMITTED ELEMENT

Furthermore, a low profile unit cell of the transmitarray lens is designed at 10GHz, as shown in Fig. 8(a)-(b). It is composed of a double metal-clad layer with a group of squares and four via holes connecting the two metal layers. The periodic structure is analyzed in full-wave simulation by placing periodic boundary conditions (PBC) around it to simulate infinite transmit array surface, as shown in Fig.8(a). Two fluent ports are placed on both sides of the unit cell to calculate the transmission coefficient, including transmission amplitude and phase respectively. Here the transmit phase shift range is obtained by using variable-size elements with varying $L$, which is the length of outer four squares. The length of the smaller square in the center is $0.25L$ and the element spacing is 20mm. The structure of double-layer
metal-clad fractal squares is printed on a 2-mm-thick substrate with a relative permittivity of 2.65 and a loss tangent of 0.005. When $L$ ranges from 3.2mm to 3.9mm, radius of via holes is also 0.2mm and $r$ is 0.4$L$. While $L$ is changed from 4mm to 8.4mm, the radius of via holes steps to 0.5mm and $r$ is varied to 0.7$L$ and $S = 0.21L$. Fig. 8(c) depicts transmission performance of the proposed transmit unit cell. It can be found when $L$ is varied from 3.2mm to 8.4mm, $310\degree$ transmit phase shift range can be obtained while transmission magnitude remains within $-3\text{dB}$. In practice, around $300\degree$ phase shift range could meet major requirements for high-gain transmitarray and reflect array antennas [26].

Fig.9 shows the variations in transmission coefficient of the transmitted element at different oblique incidence angles for TE and TM polarized incidence wave at 10GHz. The parameter $\theta$ is the elevation angle of the incident wave. From Fig.9 we can see that as the oblique incident angle becomes bigger, the transmission features of the element change. Specifically, when oblique incident angle becomes $45\degree$ at TE polarization, the insertion loss deteriorates to $-4\text{dB}$ and the transmit phase shift range decreases from more than $300\degree$ to less than $200\degree$. For TM polarization, even though the insertion loss of unit cell remains stable, the transmitted phase shift range decreases by a large margin to less than $200\degree$. For oblique incidences from $0\degree$ to $30\degree$, however, the unit cell owns relatively stable transmission coefficients except that insertion losses increase (within $-3\text{dB}$ though) and transmit phase shift shrinks (but still more than $230\degree$) at TE polarization. For TM polarization, the transmission coefficients nearly remain stable while oblique incident angle varies from $0\degree$ to $30\degree$. As a result, when the main beam of linear array is steered to more than $30\degree$, it is extremely difficult to obtain gain increment after adding the phase modulated transmitarray lens onto linear array.

Besides, transmission coefficients of transmitted element from 9.4GHz to 10.6GHz are depicted in Fig.10. It can be observed that when frequency shifts to the lower range from 9.4GHz to 9.7GHz, unit cells with smaller $L$ (smaller than 4mm) owns large insertion loss (below $-3\text{dB}$) which cannot be adopted in the transmitarray design. On the other hand, elements with bigger $L$ (bigger than 7.6mm) are out of operation also with large insertion loss when frequency moves toward 10.3GHz and 10.6GHz. Besides, the curves of transmitted phase shift deviate from that of the center frequency whether the frequencies vary from 10GHz to lower range or to higher range. Essentially speaking, the transmitarray lens is designed at one frequency point in theory which could only operate in a narrow band. Generally, the operational bandwidth of transmitarray lens is evaluated by placing it onto feed antenna, analyzing the integral performance of gain variation across the interested frequency band.
V. SIMULATION AND MEASUREMENT RESULTS

Based on the low profile transmitarray element, a one-dimensional phase modulated transmitarray lens is designed and placed above the aforementioned 1 × 8 microstrip linear array, as shown in Fig.11. Here the microstrip patch element with size of 9.9 × 7.65 mm² is printed on Rogers 4350 with thickness of 0.5mm. And the antenna element owns impedance bandwidth of 0.3GHz whose gain at 10GHz is 6.5dBi. From Fig.11 we can see that the proposed transmitarray lens performs one-dimensional phase compensation in Y-axis, and it makes minor differences to radiation patterns of linear array along X-axis because the transmission amplitude and phase of the transmit unit cell slightly vary when incident angle changes.

After adding the transmitarray lens, the wide patterns of the original linear array in the YOZ plane are transformed into narrow beams, as presented in Fig.12. And the realized maximum gains of transmitarray lens antenna under every input feed port of Rotman lens are 9.17dBi, 14.24dBi, 18.11dBi, 17.68dBi, 18.11dBi, 14.24dBi and 9.17dBi, respectively. Besides, steering angles of the main beam at each feeding port of Rotman lens are −37°, −25°, −13°, −0°, 13°, 25° and 37°, respectively.

The fabrication prototype of one-dimensional phase modulated transmitarray and microstrip linear array fed with Rotman lens is assembled and mounted onto a plastic frame, as presented in Fig.13. The transmitarray lens consists of 18 × 25 = 450 elements with total size of 360 × 500 × 2mm³. The measurement is performed in a compact anechoic chamber at 10GHz using far-field azimuth-scanning techniques. To measure gains of the antennas, inter-comparison method is utilized and an X-band standard
horn antenna is used to determine the absolute gain of antennas under test. Fig. 14(b) shows the comparison of measured radiation patterns between linear array antenna with and without one-dimensional phase modulated transmitarray lens, and simulation results are also given in Fig. 14(a) for comparison. The measurement results indicate that the realized maximum gains of original linear array under every input feed port of Rotman lens are 8.56 dBi, 8.79 dBi, 8.82 dBi, 8.83 dBi, 8.52 dBi, 8.27 dBi and 8.4 dBi at main beam steering angles of $-39^\circ$, $-25^\circ$, $-13^\circ$, $-0^\circ$, $13^\circ$, $25^\circ$ and $39^\circ$, respectively. When the one-dimensional phase modulated transmitarray lens is assembled with $1 \times 8$ linear array antenna, measured gains vary to 8.61 dBi, 13.21 dBi, 16.14 dBi, 16.48 dBi, 16.18 dBi, 11.85 dBi and 8.6 dBi at steering angles of $-39^\circ$, $-25^\circ$, $-13^\circ$, $-0^\circ$, $13^\circ$, $25^\circ$ and $39^\circ$ separately. Simulation results agree well with the measurement ones.

Maximum gain increments of 7.81 dB and 7.65 dB in simulation and measurement are obtained after adding the proposed one-dimensional phase modulated transmitarray lens onto a $1 \times 8$ microstrip linear array, indicating that fan beams in the $YOZ$ plane are transformed to pencil beams. It can be perceived that the maximum gain increments are both achieved at a direction close to boresight in simulation and measurement. Nevertheless, when beam scanning angle of the original linear array becomes wider, the gain increases slowly. Specifically, when the main beam of linear array is steered to angles larger than $37^\circ$, nearly no gain increment is obtained after adding the proposed transmitarray lens. The main reason is that aperture size of the phase modulated lens is limited which generates no phase compensation for a wide steering beam of linear array. Furthermore, from Fig.14 it can also be seen that measured gains are slightly lower than the simulated ones because that fabrication tolerance and increased loss in the measurement setup are inevitable.

VI. RADIATION EFFICIENCY AND BANDWIDTH OF TRANSMITARRAY ANTENNA

The radiation efficiency of the transmitarray lens antenna is composed of $\eta_F$, $\eta_A$ and $\eta_T$ (each of them represents feed network efficiency, radiation efficiency of linear array and transmitarray efficiency, respectively).

$$\eta = \eta_F \cdot \eta_A \cdot \eta_T$$ (4)
Generally, $\eta_F$ and $\eta_T$ is evaluated by insertion losses. Fig. 15(a) below shows radiation efficiency of linear array antenna fed by Rotman lens, and the total radiation efficiency of the transmitarray lens antenna is presented in Fig. 15(b). Each curve in Fig. 15 indicates that the linear array antenna is fed by different input port of Rotman lens. It can be seen that average radiation efficiency of 63% could be obtained for linear array antenna under every input feed port of Rotman lens at 10GHz. After adding transmitarray lens, the average radiation efficiency decreases to 50% at 10GHz which indicates that the transmitarray lens owns insertion loss with approximate 1dB as a whole.

On the other hand, since the transmitarray aperture is $360 \times 500\, \text{mm}^2$ and the maximum measured gain is 16.5 dBi. The calculated aperture efficiency of the transmitarray lens antenna is $-17.5\, \text{dB}$ or 1.78%. The low aperture efficiency can be attributed to limited illumination of the intensive $E$-field of linear array antenna on the transmitarray plane, as shown in Fig. 16. In the future, how to improve aperture efficiency of the transmitarray need to be further studied.

The operational bandwidth of return losses and radiation gains for transmitarray lens antenna under each input feed port of Rotman lens are simulated and measured in Fig. 17 and Fig. 18 from which we can see that return losses remain approximate $-10\, \text{dB}$ from 9.6GHz to 10.4 GHz in simulation and below $-10\, \text{dB}$ from 9.4GHz to 10.6GHz in measurement. The main reason why return losses are better in measurement is that dielectric and metallic losses increase in practical experiment. What’s more, when the linear array is fed by 2nd, 3rd, 4th, 5th and 6th input ports of Rotman lens, the $-3\, \text{dB}$ gain bandwidth is 8% (9.6-10.4GHz) in simulation and measurement. Specifically, when 1st and 7th input ports of Rotman lens are excited, the transmitarray antenna owns narrower gain bandwidth of 6% (9.8-10.4GHz). When scanning angles becomes larger, phase-aberrations and insertion losses of Rotman lens is bigger which causes the gain decrement. As we can see, the operational bandwidth of transmitarray lens antenna covers 0.6GHz from 9.8GHz to 10.4GHz with 6% fractional bandwidth.
This paper introduced a gain improvement principle of transmitarray for broadside linear array which could modulate a fan beam to a pencil beam by compensating phase shift for linear array on the plane orthogonal to the array axis. Rotman lens feed network is used to implement nearly \( \pm 40^\circ \) one-dimensional beam scanning for linear array with \( 1 \times 8 \) microstrip antenna elements. Then, a low profile transmitted element with one-layer of substrate is utilized to design the transmitarray which could greatly lower the fabrication expenses and difficulties. Simulations and measurements show that 7.81dB and 7.65dB gain improvement can be realized in quasi-boresight directions after adding the proposed transmitarray on the plane orthogonal to the array axis, and performance of gain improvement could be obtained within \( \pm 25^\circ \) beam scanning range. Furthermore, fan beams of the original linear array are smoothly transformed into pencil beams. The proposed transmitarray lens antenna can be used for high-gain multi-beam applications.

VII. CONCLUSION

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