Transmitarray Antenna Design Using Cross-Slot Elements With No Dielectric Substrate
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Abstract—The transmitarray antenna has received considerable attention in recent years as it combines the favorable features of the lens antenna and the array techniques. The goal of this letter is to present detailed design analysis of a multiple-conductor-layers transmitarray antenna using slot-type element with no dielectric substrate. A transmitarray antenna using quad-layer cross-slot elements has been designed, fabricated, and tested for 11.3 GHz operating frequency. The measured gain of the prototype transmitarray is 23.76 dB at 11.3 GHz. It is observed that the oblique incidence and the wave polarization have strong effect on the transmission coefficient of the slot-type element. Thus, a detailed analysis of the transmitarray considering the oblique incidence angles and the feed polarization conditions is performed with good agreement between the simulation and measured results.

Index Terms—Frequency selective surfaces (FSS), multilayer, slot-type element, transmitarray antenna.

I. INTRODUCTION

THE TRANSMITARRAY antenna concept attracts growing interest of many scientists in the antenna area. A transmitarray antenna combines the favorable features of the lens antenna that are based on optical theory and the microstrip arrays that are based on array theory, leading to a low-profile design with high gain, high radiation efficiency, and flexible radiation performance. A transmitarray antenna consists of multiple layers of flat transmitting surface and an illuminating feed source, which is located on an equivalent focal point, as shown in Fig. 1. On the transmitting surface, there is an array of antenna elements. The transmission coefficients of these elements are individually designed such that the spherical phase front from the feed source is converted into a planar phase front. As a result, a focused radiation beam can be achieved with a high gain.

There are different techniques for transmitarray designs to control the transmission phase of each unit cell in the array, aiming to obtain a transmission phase range of 360°, while maintaining the high value of the transmission magnitude. Among these techniques are the multilayer frequency selective surfaces (M-FSSs) [1]–[6] and the receiver–transmitter design [7]–[16]. The frequency selective surfaces approach controls the element transmission magnitude and phase by varying the element’s dimension. In the receiver–transmitter approach, a transmitarray antenna is typically consisting of two planar arrays of printed-type elements. One of the arrays acts as a receiver, and it is illuminated by the antenna feed source. The other array radiates into free space, and it acts as a transmitter. A coupling structure is designed between the two arrays to attain a specific phase and magnitude distribution. It is worthwhile to point out that these techniques mostly use printed-type elements mounted on substrate materials.

A cross-slot element is used in this letter to design a quad-layer transmitarray antenna. This design has a novelty in using slot-type element with no dielectric substrate, which has two main advantages. The first advantage is its suitability for space applications; this is because the conductor layers bear changes in outer space temperature compared to the dielectric substrates. The second advantage is the cost reduction because there is no need to use high-performance microwave substrate. A transmitarray antenna has been designed, fabricated, and tested at 11.3 GHz, which realizes a 23.76-dB gain.

II. CROSS-SLOT TRANSMITARRAY ANTENNA DESIGN

A. Unit Cell Element

A unit cell of a cross-slot element, as shown in Fig. 2, is simulated using CST Studio Suite software [17] at 11.3 GHz with normal incidence plane wave. Different slot length $L_s$ with periodicity $P = 0.62\lambda_0 = 16.46$ mm, and slot width $W_s = 2$ mm are considered. Quad-layer of this cross-slot element is used for this design with separation between layers equal to $H = $
$\lambda_0/4 = 6.64$ mm. This configuration has been selected based on the study of multilayer transmitarrays presented in [1] and [2]. This study illustrates that a unit cell of four identical conductor layers, separated by quarter-wavelength air gaps, can achieve a full transmission phase range of $360^\circ$ for transmission coefficients equal to or better than $-1$ dB.

Fig. 3 shows the transmission magnitude and phase versus the slot length $L_s$, which confirms the possibility of achieving $360^\circ$ transmission phase range with transmission coefficient equal to or better than $-1$ dB.

### B. Transmitarray Design and Measurements

The required transmission phase of each transmitarray element is designed to compensate the spatial phase delay from the feed horn to that element, so that a certain phase distribution can be realized to focus the beam at a specific direction, as shown in Fig. 4(a). The transmission phase $\psi_i$ for the $i$th element is calculated as

$$\psi_i = k \cdot (R_i - \hat{r}_i \cdot \hat{n})$$  \hspace{1cm} (1)

where $R_i$ is the distance from the feed horn to the $i$th element, and $\hat{r}_i$ is the position vector of the $i$th element. For a transmitarray with a main beam at the broadside direction ($\hat{r}_i \cdot \hat{n} = 0$). Once the phase is determined for the $i$th element, the corresponding slot length can be obtained from Fig. 3.

A quad-layer circular aperture transmitarray antenna of diameter $= 13.02 \lambda_0 = 34.57$ cm with the cross-slot element unit cell was fabricated for $F/D$ ratio of 0.8. It includes 325 slot elements. The feed horn is vertically polarized (along $y$-direction in the $xy$-plane) with $Q$ value equal to 6.6. Fig. 4(b) illustrates the transmitarray mask.

The antenna performances of the fabricated prototype were measured using our NSI planar near-field system shown in Fig. 5. At 11.3 GHz, the antenna shows a focused beam with a measured gain of 23.76 dB, as shown in Fig. 6. The half-power beamwidths (HPBW) are 4.6° and 8.8° in the H-plane and E-plane, respectively. The sidelobe and cross-polarized levels are $-13$ and $-30$ dB, respectively. Fig. 7 presents the transmitarray antenna measured gain versus frequency. The maximum measured gain is 24.26 dB and is located at 11.45 GHz. The 1 and 3 dB gain bandwidths are 4.2% and 9.4%, respectively.

Using the transmission magnitude and phase properties shown in Fig. 3, the array theory [18] is used to calculate the radiation pattern and gain of this transmitarray at 11.3 GHz.
These results are compared to the measured data in Fig. 6. We noticed approximately 5.2 dB differences in maximum gain and an increase of the sidelobes in the measurements compared to the theoretical results. Furthermore, asymmetric beamwidths are observed in the measured results, in spite of the symmetry of the elements along the $x$- and $y$-directions.

The differences between the measured and theoretical results are caused by the normal incidence approximation usually used for element analysis. Therefore, we have carefully studied the effect of the oblique incidence angles and the feed polarization on each array element separately.

### III. DISCUSSION ON OBLIQUE INCIDENCE AND FEED POLARIZATION EFFECTS

#### A. Unit Cell Element

First, we resimulated the unit cell element of Fig. 2, considering different values of the oblique incidence angle $\theta$, and for the elements along $x$-axis ($\phi = 0^\circ$) and $y$-axis ($\phi = 90^\circ$). For $y$-polarized incidence field, the transmission coefficient of the elements along the $x$-axis is represented by $T_{\perp\perp}$, and the transmission coefficient of the elements along the $y$-axis is represented by $T_{\parallel\perp}$. $T_{\perp\parallel}$ and $T_{\parallel\parallel}$ are the perpendicular and parallel transmission coefficient components, respectively, that are obtained from the numerical simulations.

Fig. 8 shows the variations in the transmission coefficient at different oblique incidence angles and for $y$-polarized feed horn. For the elements along the $x$-axis ($\phi = 0^\circ$), there are almost no variations in the transmission magnitude and phase, except small magnitude reduction at very small slot length $L_x$. For the elements along the $y$-axis ($\phi = 90^\circ$), and at high oblique incidence angle ($\theta = 30^\circ$), the transmission coefficient is very poor.

Due to the slot-type element configuration, each conductor layer adds some blockage on the slot elements of the following conductor layers. This blockage varies with the different oblique incidence angles and the feed polarization, which has a strong impact on the transmission coefficient of each element. However, the oblique incidence effect is usually smaller when using printed-type elements as in [4] and [5].

#### B. Aperture Distribution and Radiation Pattern

Next, we considered the effect of the oblique incidence angles on all transmitarray elements. Fig. 9 demonstrates the oblique incidence wave from the feed horn on a sample array element. The feed horn is vertically polarized and is located on the $z$-axis above the aperture center point by a focal distance $F$, such that $F/D$ ratio equals 0.8. Accordingly, each array element is fed by an oblique incidence wave defined by the angles $\theta$ and $\phi$. The incidence electric field on a certain array element can be defined by the two orthogonal components $E_{y}^i$ and $E_{x}^i$, as shown in Fig. 9. The transmitted electric field components ($E_{y}^t$ and $E_{x}^t$) from that element can be defined as

$$
\begin{bmatrix}
E_{y}^t \\
E_{x}^t
\end{bmatrix} =
\begin{bmatrix}
T_{\perp\perp} & T_{\perp\parallel} \\
T_{\parallel\perp} & T_{\parallel\parallel}
\end{bmatrix} \times \begin{bmatrix}
E_{y}^i \\
E_{x}^i
\end{bmatrix}
$$  \hspace{1cm} (2)

where $[T]$ is the transmission coefficient matrix and is obtained from the numerical simulation of the unit cell element with the consideration of the oblique incidence angles $\theta$ and $\phi$. $E_{y}^i$ and $E_{x}^i$ are obtained from the equations that describe the radiation pattern of the feed horn as functions of the angles $\theta$ and $\phi$ [19].

The transmitted vertically polarized $E_{y}^t$ and the transmitted horizontally polarized $E_{x}^t$ electric field components can then be obtained as follows:

$$
\begin{bmatrix}
E_{y}^t \\
E_{x}^t
\end{bmatrix} =
\begin{bmatrix}
\cos \phi & \sin \phi \cos \theta \\
-\sin \phi & \cos \phi \cos \theta
\end{bmatrix} \times \begin{bmatrix}
E_{y}^i \\
E_{x}^i
\end{bmatrix}.
$$  \hspace{1cm} (3)

We have resimulated each element separately at 11.3 GHz taking into account the corresponding oblique incidence angle and the feed polarization conditions. Fig. 10 compares the magnitude of the transmitted vertically polarized electric fields to both the normal incidence plane-wave approximation and the oblique incidence consideration. For normal incidence approximation, the field distribution is symmetric. Meanwhile for oblique incidence consideration, we observed a wide field distribution along the $x$-axis, and narrow field distribution along the $y$-axis. This explains the reason for the wide beamwidth in...
dielectric substrate. By varying the slot length, the element unit cell achieves 360° transmission phase range for better than 1 dB transmission coefficient. A transmitarray aperture of diameter = 34.57 cm, with 325 slot elements, achieves a measured gain of 23.76 dB at 11.3 GHz. By considering the oblique incidence angles of each array element and the feed polarization, the measured gain and the radiation patterns are closely matched with those based on theoretical analysis.

IV. CONCLUSION

This letter demonstrates a new design of a quad-layer transmitarray antenna using a cross-slot element with no Oblique incidence plane wave approximation and (b) with oblique incidence. The sidelobe level of the measured horizontal plane cut closely matched with those based on theoretical analysis. However, the vertical plane cut (yz-plane cut) and the reduction of the antenna gain.

The radiation pattern and gain have been recalculated using the array theory with oblique incidence excitation [18]. The results are depicted in Fig. 11, which shows much better agreement with the measurements. The beamwidths of the measured vertical and horizontal plane cuts almost match with the theoretical calculations. The sidelobe level of the measured horizontal plane cut conforms to the theoretical results. However, the first sidelobe level of the calculated vertical plane cut is higher than that of the measured results. This difference makes the theoretical gain a little less than the measured gain by 0.55 dB at 11.3 GHz. The theoretical and measured gains are 23.21 and 23.76 dB at 11.3 GHz, respectively. Table I presents a comparison of transmitarray measured and simulated performance.

Table I

<table>
<thead>
<tr>
<th>Description</th>
<th>HPBW (H-Plane)</th>
<th>HPBW (E-Plane)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal incidence</td>
<td>4.6°</td>
<td>4.6°</td>
<td>28.56 dB</td>
</tr>
<tr>
<td>Oblique incidence</td>
<td>4.6°</td>
<td>8.8°</td>
<td>23.21 dB</td>
</tr>
<tr>
<td>Measured</td>
<td>4.6°</td>
<td>8.8°</td>
<td>23.76 dB</td>
</tr>
</tbody>
</table>

Theoretical xz-plane Measured xz-plane Theoretical yz-plane Measured yz-plane

REFERENCES