High-Gain and Broadband Transmitarray Antenna Using Triple-Layer Spiral Dipole Elements
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Abstract—A triple-layer transmitarray antenna has been designed, fabricated, and tested at X-band. Using a spiral-dipole element, a full transmission phase range of 360° is achieved for a transmission magnitude equal to or better than −4.2 dB. The transmission phase distribution of the transmitarray elements has been optimized to reduce the effects of the lossy elements with low transmission magnitudes on the antenna gain, leading to an average element loss as low as 0.49 dB. The measured gain of the transmitarray prototype is 28.9 dB at 11.3 GHz, resulting in a 30% aperture efficiency. Antenna bandwidths of 9% for 1-dB gain and 19.4% for 3-dB gain are achieved in this design.

Index Terms—Broadband, multilayer, transmission phase range, transmitarray antenna.

I. INTRODUCTION

A PRINTED transmitarray antenna consists of a planar array of printed antenna elements and a feed source. Each element incorporates a certain transmission phase shift to produce a collimated beam in the main beam direction when it is illuminated by a feed source [1]–[3]. The relation between a reflectarray and a transmitarray is similar to the relation between a mirror and a lens. Although inspired by the reflectarray, the transmitarray encounters a great challenge for both magnitude and phase control of the element [2]–[4]. In many reflectarrays, the reflection magnitude is close to 1 (0 dB) due to the existence of a PEC ground plane [5], [6], thus one mainly needs to control the element reflection phase. In transmitarray, besides the phase control, the transmission magnitude needs to be close to 1 (0 dB) to ensure a high aperture efficiency.

A seven-conductor-layer transmitarray antenna is presented in [1] using dipole elements to achieve the full transmission phase range of 360°. In [2], a four-identical-layer transmitarray using double-square-loop element achieves full transmission phase range of 360°. To further reduce the number of conductor layers, a three-layer transmitarray antenna is designed using Jerusalem-cross elements in [3], but limiting the transmission phase range to 335° with 4.4 dB of variation in the transmission magnitude. A reconfigurable triple-layer transmitarray element achieves 360° phase range using varactor diodes in [7]. There are some designs where discrete phases states (0°/180° for 1-bit, and 0°/90°/180°/270° for 2-bit) are used for beam-steering application, at the expense of reducing the overall antenna gain [8], [9].

Hence, in order to reduce the design cost and complexity, a challenge is to achieve a full phase range of 360° using fewer conductor layers while avoiding the reduction of the element transmission magnitude and maintaining the overall performance of the transmitarray antenna. In this letter, we present a novel design of a triple-layer transmitarray antenna. Using spiral dipole elements, a full phase range of 360° is achieved for a transmission magnitude equal to or better than −4.2 dB. Furthermore, the element phase at the center of the transmitarray aperture is selected deliberately in order to reduce the effects of the lossy elements with low transmission coefficient magnitudes on the antenna gain, leading to an average element loss as low as 0.49 dB.

This design of a triple-layer transmitarray antenna using spiral-dipole elements has been fabricated and tested for X-band operation. The measured gain of the transmitarray prototype is 28.9 dB at 11.3 GHz, and the aperture efficiency is 30%. The measured 1- and 3-dB gain bandwidths are 9% and 19.4%, respectively, which are considered broadband performances as compared to the published designs in [2] and [8]–[10].

II. SPIRAL-DIPOLE TRANSMITARRAY ANTENNA DESIGN

A. Unit Cell Element

Varying the length of a conventional dipole element within a limited unit cell size (such as $\lambda_0/2$) is not sufficient to cover a full transmission phase range [4]. An extension of the dipole length can be done by bending the dipole arm. Moreover, to maintain the symmetry along the $x$- and $y$-axes, a spiral dipole shape is designed. Fig. 1 presents the spiral dipole element in three-identical-layer configuration, with unit cell periodicity of $P = 0.6\lambda_0 = 15.93$ mm. The free-space wavelength $\lambda_0$ is at 11.3 GHz. The element of each layer is mounted on a dielectric substrate of relative permittivity $\varepsilon_r = 2.574$ and thickness $T = 0.5$ mm. The separation between layers is $H = 6$ mm, such that the total separation between two layers is closer to a quarter-wavelength ($H + T \approx \lambda_0/4 = 6.64$ mm).

The antenna element is simulated using CST Studio Suite software [11]. The element structure is surrounded by periodic
boundaries on four sides and absorbing boundaries on top and bottom surfaces. A normal incidence plane wave is used to illuminate the element, and the transmission coefficient is obtained. Various dimensions of length \(L\) and width \(W = 0.1L\) are considered. Fig. 2(a) presents the transmission magnitude and phase versus the element dimension \(L\) at 11.3 GHz. A full transmission phase range of 360° is achieved with transmission magnitude equal to or better than \(-4.2\) dB. Furthermore, a 270° phase range is achieved with magnitude better than \(-1\) dB, and a 320° phase range is achieved with magnitude better than \(-3\) dB. It is worthwhile to emphasize the relation between the transmission magnitude and phase. Fig. 2(b) depicts the phase magnitude relationship in a polar diagram with the variation of the element dimension, such that the magnitude represents \(|S_{21}|\) and the angle represents \(\angle S_{21}\). The result agrees well with the theoretical analysis in [4].

The element width of \(W = 0.1L\) is selected to maintain a large range of variation in the element length \(L\), and hence a more linear slope is achieved, as shown in Fig. 2(a). The length \(L\) varies between 6.65 and 14.65 mm to obtain the full transmission phase range of 360°, which makes the design less sensitive to manufacturing error.

It is usually assumed in the design of transmitarray antennas that the feed signal is normally incident on all elements, although the majority of the elements are actually illuminated by oblique incidence angles. Thus, it is worthy to present the behavior of the spiral dipole element under oblique incidence. Fig. 3 depicts the variations in the transmission magnitude and phase at different oblique incidence angles and for \(y\)-polarized incidence signal. The parameters \(\phi\) and \(\theta\) are the azimuth and elevation angles, respectively, of the incidence wave. For the E-plane (\(\phi = 90°\)), there are almost no variations in the transmission magnitude and phase, except small changes at large element dimensions (\(L > 13\) mm) and with oblique incidence as high as \(\theta = 30°\). For the H-plane (\(\phi = 0°\)), and with the increase of the oblique incidence angle \(\theta\), we noticed not only phase changes but also magnitude reduction at certain values of the element dimension \(L\).

### B. Transmitarray Design

The transmission phase of each transmitarray element is designed to compensate for the differential phase delay from the illuminating feed. Thus, the required element transmission phase is not an absolute value, but it is relative to the transmission phases of the neighbor elements. The required transmission phase \(\psi_i\) for the \(i\)th element is calculated as

\[
\psi_i = k(R_i - \hat{r}_i \cdot \hat{r}_0) + \psi_0
\]  

(1)

where \(k\) is the propagation constant, \(R_i\) is the distance from the feed horn to the \(i\)th element, \(\hat{r}_i\) is the position vector of the \(i\)th element, and \(\hat{r}_0\) is the main beam unit vector, as shown in Fig. 4. For a transmitarray with a main beam at the broadside direction, \(\hat{r}_0 \cdot \hat{r}_0 = 0\). \(\psi_0\) is a phase constant that is selected to drive the reference phase at the aperture center \(\psi_c\) to a certain value.
Once the \(i\)th element phase is determined, the corresponding element dimension \(L\) can be obtained from Fig. 2(a). Equation (1) does not consider the phase of the horn pattern, the oblique incidence, and the feed polarization, while an approximation is usually used in practical designs in determining the phase of the unit-cell element for simplicity.

A triple-layer circular aperture transmitarray antenna of \(\text{diameter} = 16.2\lambda_0 = 43.61\) cm using the spiral-dipole elements was designed for an F/D ratio of 0.8. It includes 537 elements. The feed horn is vertically polarized (along the \(-d\) direction in the \(xy\)-plane) with a gain equal to 15.9 dB at 11.3 GHz. The feed horn pattern is approximately modeled as \(\cos^2(\theta)\), where \(g = 6.6\). Referring to Fig. 2(b), the transmission phase of the transmitarray center element is selected at \(\psi_c = 55^\circ\), which has a transmission magnitude equal to 1 (0 dB). Consequently, when the element is away from the aperture center, it needs a transmission phase larger than 55°, thus moving counterclockwise in the polar diagram of Fig. 2(b). The transmission magnitudes of these elements are still closer to 1 (0 dB) until the element transmission phase is larger than 300°, which has a transmission magnitude less than –1 dB [see Fig. 2(b)]. The aim of this phase distribution is to keep the lossy elements, which have low transmission magnitudes, away as much as possible from the aperture center, thus reducing their contribution to the average element loss. This is because the radiation pattern of the feed antenna is directed with its maximum power to the center of the transmitarray aperture, while the feed illumination decreases away from the aperture center.

The average element loss is calculated for different values of the center element phase \(\psi_c\), as shown in Fig. 5. The average element loss is calculated as

\[
\text{EL}_{\text{avg}} = \frac{\sum_{i=1}^{N} I_i^2 \cdot T_i}{\sum_{i=1}^{N} T_i}
\]

where \(I_i\) and \(|T_i|\) are the illumination and transmission magnitude of the \(i\)th element, respectively. The parameter \(N\) is the total number of elements. It is observed from Fig. 5 that the average element loss is minimum with 0.49 dB when \(\psi_c = 55^\circ\), as expected from previous discussion.

Fig. 6(a) presents a top view picture of the fabricated transmitarray aperture. The transmission phase distribution of the transmitarray is shown in Fig. 6(b) with element phase of 55° at the aperture center. Fig. 6(c) presents the transmission magnitude distribution, which demonstrates the high values of those elements close to the aperture center. Fig. 6(d) presents the relative illumination from the feed on the transmitarray elements. It illustrates the concentration of the feed illumination around the aperture center, with illumination taper at the edge of the transmitarray aperture equal to –10.2 dB.

III. EXPERIMENT AND DISCUSSION

The NSI planar near-field system is used to measure the antenna performances of the fabricated prototype, as shown in Fig. 7. At 11.3 GHz, the antenna shows a focused beam, as shown in Fig. 8. The measured directivity and gain at 11.3 GHz are equal to 30.2 and 28.9 dB, respectively. Thus the measured radiation efficiency (gain over directivity ratio) is equal to 74%. The HPBW are 4.0° and 5.0° in the E-plane \((yz\)-plane\) and H-plane \((xz\)-plane\), respectively. The sidelobe and cross-polarized levels are –21 and –27 dB, respectively, in both planes. The corresponding aperture efficiency \(\eta_{\text{ap}}\) is calculated using

\[
\eta_{\text{ap}} = \frac{G}{D_{\text{max}}} \quad D_{\text{max}} = \frac{4\pi A}{\lambda_0}
\]
where $G$ is the measured gain, $D_{\text{max}}$ is the maximum directivity, $A$ is the area of the antenna aperture, and $\lambda_0$ is the free-space wavelength. The aperture efficiency is found to be 30%. The pattern beamwidths in E-plane and H-plane are different due to the oblique incidence angle and the linear polarization of the feed horn. Detailed analysis of this observed characteristic can be found in [12].

The measured gain of the transmitarray antenna versus frequency is presented in Fig. 9. The 1- and 3-dB gain bandwidths are 9% and 19.4%, respectively, which are considered broadband performance achieved using a triple-layer configuration. For all frequencies within the 3-dB gain bandwidth, the radiation patterns have sidelobe and cross-polarized levels better than $-14$ and $-21$ dB, respectively. Table I compares these results to recent published work.

IV. CONCLUSION

This letter demonstrates a design of a broadband high-gain transmitarray antenna using only three conductor layers of spiral-dipole elements. The spiral-dipole element achieves a 360° transmission phase range with a transmission magnitude better than or equal to $-4.2$ dB. It has large range of variation in the element dimensions, creating a more linear slope for the phase, which makes the design less sensitive to manufacturing error. The element phase distribution on the transmitarray aperture is optimized to decrease the loss due to the elements having small transmission magnitudes, leading to an average element loss as low as 0.49 dB. A transmitarray antenna with a diameter of 43.01 cm (16.2A$_0$) at 11.3 GHz, consisting of 537 spiral dipole elements, is fabricated and tested. It achieves a measured gain of 28.9 dB at 11.3 GHz and a broadband of 9% at 1-dB gain and 19.4% at 3-dB gain.

ACKNOWLEDGMENT

The authors gratefully acknowledge the generous contribution of ANSYS, Inc., and Intel Corporation to Colorado School of Mines.

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