A single layer delay-lines based reflectarray for X-band applications

Tayyab Shabbir1a), Rashid Saleem1, Sabih Ur Rehman2, and Muhammad Farhan Shafique3

1 Department of Telecommunication Engineering, University of Engineering and Technology, Taxila, 47050, Pakistan
2 School of Computing and Mathematics, Charles Sturt University, Australia
3 Center for Advanced Studies in Telecommunication (CAST), COMSATS Institute of Information Technology, Park Road, Tarlai Kalan, Islamabad 45550, Pakistan

a) Tayyab.Shabbir@uettaxila.edu.pk

Abstract: This paper presents a single-layer delay-lines based reflectarray for X-band applications. The proposed design contains an octagonal-shaped patch with T-shape delay-lines. A phase range of 500° is realized by using T-shape delay-lines. A stable phase range is achieved for TE and TM modes at 0°, 15° and 30° incident angles. An equivalent circuit model is used to investigate the resonant property of the proposed reflectarray unit element. A 21 × 21 elements reflectarray is designed, fabricated and measured on an FR-4 substrate. The proposed design provides 1-dB gain bandwidth of 18.5% and 3-dB gain bandwidth of 30%. Measured gain of 26 dBi at 10 GHz with aperture efficiency of 65% is obtained. The proposed reflectarray configuration have side-lobe-levels less than −25 dB.

Keywords: reflectarray, equivalent circuit modeling, high gain, phase range

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

1 Introduction

Traditionally, high gain was achieved by employing parabolic reflectors and phased-arrays. Phased-arrays have complex feed networks that are associated with high losses whereas the parabolic reflectors have limited beam scanning capability and are difficult to fabricate at higher frequencies due to excessive miniaturization [1]. However, reflectarrays do not have disadvantages associated with parabolic reflectors and phased-arrays and are proven to be a good alternative to parabolic reflectors as well as phased-arrays [2]. Reflectarray are low profile, light-weight, inexpensive and have less fabrication complexity due to their planar layouts [3]. Reflectarrays comprise of flat reflecting surface and are illuminated by a feed horn antenna. This surface reflects and directs the waves in desired direction to form a highly directive far-field radiation pattern [4, 5].

However, among all these advantages, there are some limitations of reflectarray antennas. One of the shortcomings of a reflectarray antenna is narrow bandwidth. This narrow bandwidth is due to the inherent narrow-band response of radiating array elements. In order to overcome these limitations of reflectarrays, numerous methods have been proposed such as using multi-layer structures, employing thicker substrate and attaching delay lines [1, 4, 6]. With these methods, linear phase responses can be achieved so as to improve the bandwidth of reflectarrays. Single-layer reflectarrays with attached delay-lines are reported in the literature owing to broad linear phase range, lower fabrication errors and cost [7].
In this letter, delay-lines based reflectarray is presented. The reflectarray is designed for X-band applications with a center frequency of 10 GHz. The proposed array cells comprise of octagonal patch joined to T-shaped delay-line. The proposed reflectarray is designed and optimized by using Ansys High Frequency Structure Simulator (HFSS™).

2 Unit cell design and analysis

The reflectarray unit cell configuration, equivalent circuit analysis and performance parameters are discussed in this section.

2.1 Reflectarray unit cell configuration

The reflectarray unit cell is designed on an FR-4 substrate. The dielectric substrate has loss tangent $\tan \delta = 0.02$ and dielectric constant $\varepsilon_r = 4.4$. The proposed unit element configuration is shown in Figs. 1a and 1b.

![Unit element configuration](image)

The design top layer comprises of delay-line based octagonal patch while air-gaped ground plane is placed on the flip side of substrate. The optimized unit element parameters to obtain 500° phase range are $D_x = 10 \text{ mm}$, $D_y = 10 \text{ mm}$, $L_1 = 8 \text{ mm}$, $L_2 = 2.7 \text{ mm}$, $L_3 = 2.7 \text{ mm}$, $L_4 = 3.43 \text{ mm}$, $W_1 = 0.38 \text{ mm}$, $W_2 = 0.4 \text{ mm}$, $W_3 = 0.4 \text{ mm}$, $G_1 = 0.3 \text{ mm}$, $T = 1.6 \text{ mm}$ and $H = 3.75 \text{ mm}$. The octagonal shaped patch with delay-lines based unit cell is chosen because it provides broad phase range and low side-lobe-levels. The unit cell optimizations are performed using Finite Element Method (FEM) incorporated in Ansys High Frequency Structure Simulator (HFSS). The Floquet port is used with master-slave boundaries. The structural view of unit cell along with HFSS simulation setup is shown in Fig. 1c.

2.2 Equivalent circuit analysis

The equivalent circuit model approach is used to investigate the resonant behavior of the proposed reflectarray unit element [8, 9]. The circuit model of the reflectarray unit cell along with air-gaped ground plane is depicted in Fig. 2.

The impedance of proposed octagonal patch with delay-lines is represented by $Z_{in}$. The equivalent circuit model consists of a series $L_uC_u$ branch that represents
T-shaped delay-line and periodicity/gap between adjacent array elements. The $L_b C_b$ branch represents the slotted octagonal patch. The resistor $R$ represents the ohmic losses in the radiating patch, which are ignored for the sake of simplicity. The unit element impedance $Z_{\text{in}}$ is derived through equivalent circuit modeling and is given by Eqn. 1,

$$Z_{\text{in}} = \frac{\alpha^2 C_a L_b - (1 - \alpha^2 C_a L_a)(1 - \alpha^2 C_b L_b)}{j\alpha C_a (1 - \alpha^2 C_b L_b)}.$$  

(1)

According to [7, 8], reflection coefficient can be computed by the following relationship provided in Eqn. 2,

$$\Gamma = \frac{Z_{\text{in}} Z_L - (Z_a Z_L + Z_c Z_{\text{in}})}{Z_{\text{in}} Z_L + (Z_a Z_L + Z_c Z_{\text{in}})}.$$  

(2)

It is important for many reasons, including but are not limited to controlling the unit element resonant frequency, to calculate the values of the equivalent circuit capacitances and inductances. The lumped components values are computed by using equivalent circuit model procedure presented in [10]. The optimum lumped components values for 10 GHz frequency are $L_a = 0.64 \text{nH}$, $L_b = 0.47 \text{nH}$, $C_a = 0.60 \text{pF}$ and $C_b = 6.6 \text{pF}$. The equivalent circuit model and simulated HFSS resonance of proposed unit cell is shown in Fig. 3a.

### 2.3 Unit cell performance parameters

Reflectarray unit cell performance is investigated in terms of reflection amplitude, reflection phase range and oblique incident angles in transmission modes. Reflection amplitude against delay lines length, $L_1$, is given in Fig. 3a. The reflection curve shifts towards lower frequencies as the length of delay-line, $L_1$, increases and moves towards higher frequencies when length of delay-line, $L_1$, decreases. The circuit model and HFSS reflection amplitude of unit cell is also depicted in Fig. 3a.

The phase range at 9, 10 and 11 GHz is depicted in Fig. 3a. The minimum phase range of reflectarray unit cell should be greater than $360^\circ$ to obtain correct phase transformation in full reflectarray configuration. A phase range of more than $500^\circ$ at 10 GHz is achieved by changing the length of delay-line, $L_1$, from 0 to 8 mm. The phase curves are linear and parallel, which shows the broadband property of reflectarray unit cell. The oblique incident angle effect at $0^\circ$, $15^\circ$ and $30^\circ$ is observed in TE and TM modes. A stable angular phase range (less sensitive
to the angle of incidence variations) is observed as shown in Figs. 3b and 3c. To investigate the effect of unit cell design parameters on phase range, a parametric analysis is performed at 10 GHz. By increasing the delay-lines width ($W_3$) and gaps in truncated octagonal patch ($G_1$), the phase curve moves towards higher frequencies, as shown in Fig. 4a. The effect of changing the ground plane height, $H$, is illustrated in Fig. 4b. The maximum linear phase curve is achieved at 3.75 mm. The phase curve becomes steeper by increasing the distance beyond 3.75 mm. Strong surface currents and electric fields are observed on the delay-line at 10 GHz, which shows the importance of delay-lines for achieving broad phase range, as shown in Figs. 4c and 4d.

3 Reflectarray configuration

A 21 × 21 elements reflectarray is designed on FR-4 substrate. The array elements are equally spaced with inter-element spacing of 0.33λ₀ [1]. The inter-element spacing is commonly kept less than half the free space wavelength, to prevent emergence of the grating lobes [1, 3]. The proposed reflectarray is illuminated by a feed horn antenna with $F/D$ ratio of 1.0. This is ratio of feed horn focal length ($F$) to the aperture diameter ($D$) of reflectarray. The array elements are placed on top layer and ground plane is placed on the bottom of the substrate which limits the scattering in lower half. The required phase distribution on array elements is calculated by using Eqn. 3 [3].
Here, $\phi_R(x_i, y_i)$ represents phase distribution on the array aperture, $k_o = 2\pi/\lambda$ shows the free space propagation constant in vacuum, $(\phi_b, \theta_b)$ is the array main beam direction, $(x_i, y_i)$ are the array elements coordinates and $d_i$ is distance from feed horn to reflectarray center. The feed horn is placed 210 mm away from array aperture. The phase distribution on reflectarray aperture is given in Fig. 5a. This phase distribution plot is used to determine the length of each array phase shifting element, to obtain a confined beam in the far-field region.

$$
\phi_R(x_i, y_i) = k_o[d_i - (x_i\cos\phi_b + y_i\sin\phi_b) \times \sin\theta_b].
$$

Fig. 4. Parametric analysis and surface currents: (a) parametric analysis at different design parameters (mm) (b) ground plane effect (c) J-surf (d) E-field

Fig. 5. Phase distribution and FEBI simulations: (a) Phase distribution on reflectarray aperture, (b) FEBI based $21 \times 21$ elements reflectarray simulations.
3.1 Reflectarray system simulations

The reflectarray system simulations are performed by using hybrid Finite Element Boundary Integral (FEBI) method given in HFSS. This method combines the features of Finite Element and Integral Equations methods, to provide efficient simulation solution for electrically medium to large structures. The FEBI based reflectarray configuration along with feed horn is shown in Fig. 5b. The reflectarrays require high computational resources and time due to large apertures. The simulations are performed on a 16-cores HP Z840 desktop workstation with RAM of 64 GB. The system took about 20 hours to simulate the reflectarray. The reflectarray FEBI system model is used to obtain far field radiation characteristics [11].

3.2 Fabrication and measurements

The fabricated reflectarray prototype is shown in Fig. 6. The fixture is made out of wood which provides low reflections in the measurements. The front side of the fixture is designed to hold the feed horn antenna. The rear side of fixture holds the reflectarray unit cells and air-gaped ground plane. A Lucas Nuelle® WR90 horn with 10 dBi gain operating in X-band (8 to 12 GHz) is employed as a feed antenna. The normalized simulated and measured E and H-plane radiation patterns at 10 GHz are depicted in Figs. 7a and 7b. The side-lobe-levels are less than −25 dB and cross polarization levels are below than −45 dB in both planes. The simulated and measured gain against frequency is shown in Fig. 7c. The proposed reflectarray prototype provides a measured gain of 26 dBi with aperture efficiency of 65% at X-band center frequency of 10 GHz. The 1-dB gain bandwidth of 18.5% (9.25–11.10 GHz) and a 3-dB gain bandwidth of 30% (8.5–11.5 GHz) is achieved for the proposed design. The comparison of the proposed reflectarray with related reported literature is given in Table I.
4 Conclusion

An octagonal patch reflectarray with T-shaped delay-lines is presented in this paper. A broad linear phase range of 500° is achieved by changing the length of delay-lines and height of air-gaped ground plane. The unit element resonance behavior is also analyzed in terms of equivalent circuit model. A 21 × 21 elements reflectarray is fabricated and measured with an $F/D$ ratio of 1. The reflectarray system simulations are performed by using hybrid FEBI method. A measured gain of 26 dBi is achieved. The proposed design provides 1-dB and 3-dB bandwidth of 18.5% and 30% respectively. The side-lobe-levels are less than −25 dB in both $E$ and $H$-planes. The reflectarray performance is analyzed in terms of reflection phase range, equivalent circuit model and oblique incidence effect.

Table I. Proposed reflectarray comparision with literature

<table>
<thead>
<tr>
<th>References</th>
<th>[This work]</th>
<th>[12]</th>
<th>[13]</th>
<th>[14]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central frequency (GHz)</td>
<td>10</td>
<td>7.25</td>
<td>10</td>
<td>13.5</td>
</tr>
<tr>
<td>Gain (dBi)</td>
<td>26</td>
<td>23.7</td>
<td>26.1</td>
<td>25</td>
</tr>
<tr>
<td>Aperture efficiency (%)</td>
<td>65</td>
<td>36</td>
<td>40.3</td>
<td>39</td>
</tr>
<tr>
<td>Cross-polarization (dB)</td>
<td>−40</td>
<td>−20</td>
<td>−23</td>
<td>−35</td>
</tr>
<tr>
<td>3-dB gain bandwidth (%)</td>
<td>30</td>
<td>19.8</td>
<td>28</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 7. Far-field radiation characteristics: (a) $E$-plane, (b) $H$-plane, (c) gain at 10 GHz.