Beam steering of Array Antenna with 2-orthogonal-I-shaped Defected Ground Structure

Conference Paper - January 2016
DOI: 10.1109/APACE.2016.7656451

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Beam Steering of Array Antenna with 2-Orthogonal-I-Shaped Defected Ground Structure*

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Abstract — Embedding of Defected Ground Structure (DGS) into a Microstrip Phased Array Antenna (MPAA) gives encouraging alterations on orientation of main beam. In this study, exploration on the development of a 2 x 1 rectangular patches operating at 8.88 GHz is discussed. The two rectangular patches are separated at 0.3877λ, and the microstrip line is fed to midpoint of the patches to optimize impedance matching. Thereafter, two-orthogonal-I-shaped DGS (2-OI-DGS) is inserted into the midst the two patches at ground plane. It has been observed that by adjusting dimension of the DGS, main lobe of the MPAA decreases from 15° to -29°, and directivity of the arrays maintains around 7.48 dBi. This explains the prospect of utilizing DGS to lead main beam of MPAA rather than employing additional phase shifter, which is massive and more sophisticated to be fastened to the antenna’s feeding line.

Keywords — array antenna; beam steering; defected ground structures (DGS).

I. INTRODUCTION

The necessity for a cheap and sturdy Phase Array Antenna (PAA), yet simple to work at microwave and millimetre wave frequencies has risen recent years. A steerable antenna with tuneable phase shifter continues to be a popular choice for radio operators to provide such systems. On the other hand, the supplementary equipment make the system complex, hulking and incur fabrication cost. Thus, it creates new challenges for antenna styler to find new equipment that are able to provide an identical feature yet gives similar performance. One of them is an employment of DGS at RF front-ends circuit to support different beam angles. This leads to new perspective on the improvement of beam steering. This means changing direction of main lobe of radiation pattern, where the antennas are able to adjust the beam dynamically towards the target of interest.

PAA is a critical component in many radar and communication systems [1] and has had many improvements over a single element. Weighting the signal before collecting them enables reinforced performance characteristics, such as interference rejection and beam steering without physically moving the aperture [2]. Microstrip array antennas are widely used due to their engaging features such as ease to manufacture, low profile, small physical size, light weight, and low cost [3].

Incorporating of DGS in MPAA system has already shown capability to minimize mutual coupling as well as improving radiation patterns [4]-[8], cross polarization reduction [9]-[10], circuit size reduction [11], harmonic frequencies suppression [12], and mitigation of back-and side-lobe [8],[13]. Several phase shifters have also been suggested based on the DGS, which is primarily used in filter, coupler, and oscillator designs [14]. DGS disturbs the current allocation direction and it is usually positioned on the ground plane. This disturbance modifies electrical characteristics of the transmission line by tampering capacitance and inductance in the representation of equivalent circuit to procure slow-wave effect and band-stop property [11]. As a result of this slow-wave effect, the electrical lengths of the microstrip lines, which are combined by DGS in matching networks, are longer than the original ones [15]-[16].

In this paper, we proposed 2-OI-DGS as phase shifter for beam steering applications. This paper is organized as follows; the array antenna design is presented in Section II, the simulated results are given in Section III. In Section IV, the orientation main beam of MPAA without DGS is compared with that with 2-OI-DGS. In Section V, another comparison is conducted to observe the effect of DGS on surface current distribution.

II. ARRAY ANTENNA DESIGN

Fig. 1 (a) depicts an MPAA without DGS. The structure includes a 2x1 rectangular element patch array, 50 Ω microstrip feed line on Roger board with a relative permittivity of 2.2, loss tangent of 0.009 and a thickness of 1.575 mm. The ground plane dimension is 48.4 mm x 19.55 mm. Both elements have equal dimension of width, 11.1
mm and length, 10.2 mm and each is separated by a 13.1 mm spacing, as illustrated in Table I. The SMA-port excitation is utilized in simulation. The simulations have been carried out using the frequency domain solver in CST MWS with open (add space) boundary conditions.

Later, the 2-OI-DGS are inserted on the ground plane of the MPAA with a dimension of 18 mm x 10.6 mm, as depicted in Fig. 1 (b). The distance of DGS and the edge of radiation element are optimized through the parametric study to 1.25 mm.

### TABLE I. DESIGN SPECIFICATION OF RECTANGULAR PATCH

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate type</td>
<td>Roger, loss tangent of 0.0009</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>2.2</td>
</tr>
<tr>
<td>Centre frequency (GHz)</td>
<td>8.91</td>
</tr>
<tr>
<td>Substrate height (h)</td>
<td>1.575</td>
</tr>
<tr>
<td>Patch thickness</td>
<td>0.035</td>
</tr>
<tr>
<td>W</td>
<td>11.1</td>
</tr>
<tr>
<td>L</td>
<td>10.2</td>
</tr>
<tr>
<td>W_{grd}</td>
<td>48.4</td>
</tr>
<tr>
<td>L_{grd}</td>
<td>19.55</td>
</tr>
<tr>
<td>R</td>
<td>13.1</td>
</tr>
<tr>
<td>W_g</td>
<td>1.6</td>
</tr>
<tr>
<td>L_g</td>
<td>5.1</td>
</tr>
</tbody>
</table>

### III. SIMULATED RESULTS

The 2-OI-DGS, as depicted in Fig. 2 with a dimension of 10.6 mm x 18 mm are incorporated on the ground plane between two radiated elements with 4 mm separation in vertical direction. The separation of 4 mm, the size of the OI-DGS, as well as the separation between OI-DGS and the edge of radiation element are very important to get beam steering because with appropriate location and size, DGS slot can offer a beam steering [17]-[18]. The open (add space) borders are picked at the top and the bottom sides for z-direction with separation to the reference plane of 5.304 h (or -8.3275 mm). For x- and y-direction, the electric boundary condition, \( E_{tan} = 0 \) and magnetic boundary condition, \( H_{tan} = 0 \), the waveguide port excitation is used in simulation to get the 2-OI-DGS characteristics.

Fig. 2. Layout of the 2-OI-DGS.

The dimension of \( b \) is varied at 3 different values, namely 5.44 mm, 7 mm and 8 mm, while keeping other values constant. Resonant frequency of the 2-OI-DGS falls between 8.948 GHz and 8.822 GHz when \( b \) increases from 5.44 mm to 8 mm, as depicted in Fig. 3 (a). The impact of changing the size of DGS is the key parameter that alters the resonant frequency [19].

Reflection phase perspective is depicted in Fig. 3 (b) without DGS, the ground plane reflects incoming signal at 180° without losses. When \( b = 5.44 \) mm, the reflection phase about the 2-OI-DGS resonant frequency of 8.948 GHz increases from 106.87° to 250.95° within the frequency band between 8.94 GHz and 8.954 GHz. When \( b = 7 \) mm, about resonant frequency of 8.904 GHz, the phase decreases from 69.73° to -77° within the frequency band between 8.9 GHz and 8.907 GHz. When \( b = 8 \) mm, about resonant frequency of 8.822 GHz, the phase decreases from 78.63° to -76.25° within the frequency band between 8.814 GHz and 8.828 GHz. It can be observed that the reflection phase experience significant change at DGS resonant frequencies, which implies greater phase range. As it has been known, the phase range is maximum for an ideal slope of 90°, while for ideal slope of 0°, the phase range is 0°, as depicted in Fig. 3 (b) for the ground plane without DGS. The objective here is to obtain significant phase change to get beam steering. The significant variation in reflection phase of the DGS at resonant frequency proves the possibility of DGS to be applied as an alternative phase shifter and contributing to beam steering ability in MPAA.
Fig. 3. Parametric analysis of length \( b \) of the 2-OI-DGS (a) reflection magnitude, (b) reflection phase.

Fig. 4 depicts return losses of the planar arrays without DGS, which resonates at 8.91 GHz with a return loss of -17.44 dB, while the resonant frequency of the antenna arrays shifts from 30 MHz downwards from 8.91 GHz to 8.88 GHz with return losses of -17.65 dB after inserting the 2-OI-DGS for \( b = 5.44 \) mm due to slow-wave effects [5]. The detailed changes in the resonant frequency of the rectangular patches are tabulated in Table II below. Therefore, later analysis on the planar arrays with 2-OI-DGS slots is carried out at the resonant frequencies at 8.88 GHz, 8.83 GHz and 8.81 GHz for MPAA with different values of \( b \) 5.44 mm, 7 mm and 8 mm, respectively.

<table>
<thead>
<tr>
<th>( b ) (mm)</th>
<th>( f ) for 1st element</th>
<th>( f ) for 2nd element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DGS</td>
<td>8.91</td>
<td>8.91</td>
</tr>
<tr>
<td>With DGS</td>
<td>8.88</td>
<td>8.87</td>
</tr>
<tr>
<td>5.44 mm</td>
<td>8.83</td>
<td>8.83</td>
</tr>
<tr>
<td>7 mm</td>
<td>8.81</td>
<td>8.81</td>
</tr>
<tr>
<td>8 mm</td>
<td>8.81</td>
<td>8.81</td>
</tr>
</tbody>
</table>

IV. BEAM STEERING ACHIEVEMENT

Table III summarizes directivity of planar array, the direction of main lobe and gain at side lobe. Without having DGS, the main beam is steered to 15° at 8.75 dBi with side lobe gain of -5.2 dB. The direction change of main beam is comparatively small when \( b = 8 \) mm because the 2-OI-DGS resonant frequency is far apart from rectangular patches’ resonance, the beam direction decreases to 11°, and the gain of planar array decreases to 8.46 dBi with side lobe gain of -4.9 dB, as depicted in Fig. 5 (a). When \( b = 7 \) mm, the beam direction decreases to 14°, and the overall gain decreases to 8.44 dBi with side lobe gain -4.6 dB. For \( b = 5.44 \) mm, a considerable change to the main beam direction is noted at -29°, and directivity of the gain relatively maintains at 7.48 dBi without side lobe. As described previously, the resonant frequency of the 2-OI-DGS of 8.948 GHz is close to the resonant frequency of the rectangular patches 8.91 GHz, therefore the considerable change in the reflection phase of the 2-OI-DGS gives 44° change in beam direction of the planar antenna array, as depicted in Fig. 5 (b). This is to guarantee that the considerable change in reflection phase of DGS causes large changes in beam orientation of the planar antenna arrays. Therefore, the ideal dimension of \( b \) is 5.44 mm, where the 2-OI-DGS provides maximum beam steering without side lobe level.

As mentioned in section III, resonant frequency of the 2-OI-DGS falls from 8.948 GHz to 8.822 GHz when \( b \) increases from 5.44 mm to 8 mm, which signifies the
resonance of the proposed DGS is inversely proportional to length $b$ because it increases the effective series inductance of the line. The impact of the proposed DGS is also obvious in reducing side lobe.

**TABLE III. BEAM STEERING CAPABILITY FOR DIFFERENT $b$**

<table>
<thead>
<tr>
<th>$b$ (mm)</th>
<th>Directivity D (dBi)</th>
<th>Main lobe direction</th>
<th>Sidelobe (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DGS</td>
<td>8.75</td>
<td>15°</td>
<td>-5.2</td>
</tr>
<tr>
<td>With DGS</td>
<td>5.44</td>
<td>7.38</td>
<td>-14°</td>
</tr>
<tr>
<td>7</td>
<td>8.44</td>
<td>14°</td>
<td>-4.6</td>
</tr>
<tr>
<td>8</td>
<td>8.46</td>
<td>11°</td>
<td>-4.9</td>
</tr>
</tbody>
</table>

This investigation has shown the ability of the 2-OI-DGS to manipulate main beam of two rectangular patches. The simulated results depict a small reduction in the directivity gain contributed by the DGS; note that main beam width comparatively wide beam, but this can enhanced further by increasing the number of antenna elements. The same structure can be used in [5]-[8], [20]-[21] for mutual coupling minimization. Definitely, there is no reduction in mutual coupling for the value of $b = 5.44$ mm, as depicts in Fig.6, but we can use this design for frequencies more than 8.88 GHz as long as the $S_{11}$ is still below -10 dB, as depicted in Fig. 4.

![Fig. 5. Radiation pattern, plane $\phi = 90°$ (x-y plane) without DGS at 8.91 GHz and with 2-OI-DGS at 8.81 GHz, $b = 8$ mm, (b) without DGS at 8.91 GHz and with 2-OI-DGS at 8.88 GHz, $b = 5.44$ mm.](image)

V. **SURFACE CURRENT DISTRIBUTION**

Fig. 7 exhibits the surface current apportionment on rectangular patches, without and with 2-OI-DGS at 8.91 GHz and 8.88 GHz, respectively, when one element is excited while the second patch antenna is terminated with a 50 $\Omega$ load. Without DGS, the maximum surface current of 160.7 A/m occurs near the edges of the rectangular patch. After addition of 2-OI-DGS $b = 5.44$ mm, maximum surface current increases to 161.2 A/m, where it flows around the upper and lower OI-DGS.

![Fig. 6. Mutual coupling comparison for MPAA, with and without DGS.](image)

![Fig. 7. Surface current distribution.](image)
Fig. 7. Snapshot of surface current distribution on ground plane at (a) 8.91 GHz without DGS, (b) 8.88 GHz with 2-OI-DGS.

VI. CONCLUSION

A design of 2×1 rectangular patches combined with 2-OI-shaped DGS slot has been realized. The 2-OI-DGS are located between two patches. The proposed design evaluates the possibility to lead a beam steering of the MPAA at 8.88 GHz. The beam orientation depends on slot length $b$. The proposed structure legalizes beam scanning from 15° without DGS to -29° with 2-OI-DGS $b = 5.44$ mm. Simulated results have indicated a small lessening in directivity gain due to the use of DGS, but this may be recovered further by adding more radiated elements.

REFERENCES