CHAPTER 5

WIDEBAND GRID ARRAY ANTENNAS FOR AUTOMOTIVE RADAR SYSTEMS

5.1 AUTOMOTIVE RADAR TECHNOLOGY

As a part of ITS, the present generation automobiles deploy sensing systems to monitor the driving environment to increase the safety aspects of the passengers. The sensing systems are assisted by technologies such as radio detection and ranging (Radar), light detection and ranging (Lidar), ultrasound, video camera, 3D camera and far infra red (IR) camera. Of all these technologies, the radar system gains higher interest due to its stability in detecting targets during inclement weather conditions such as rain and snow (Honma & Uehra 2001).

The interest on automotive radar technology at microwave frequencies began in 1970s. However, these automotive radar systems are launched in market during late 1990s after the advent of new semiconductor technologies and digital signal processing units. During its development, the interest is concerned mainly at 17 GHz, 24 GHz, 35 GHz, 49 GHz, 60 GHz and 77 GHz frequency spectrum. Many premium car manufacturers such as Mercedes, Nissan, BMW and Audi integrate radar technology to simultaneously provide both passengers and drivers with comfort and safety. Some of the potential applications during the evolution stages include ACC and automatic brake assist for collision avoidance. In addition to these, the
The two most popular millimeter wave automotive radars are Long Range Radar (LRR) and Short Range Radar (SRR) systems. The LRR operating at 24/77 GHz frequency spectrum is characterized by narrow beams to control the driving path in the front of the car and to estimate the relative distance between the car and the vehicle ahead of it. This ensures a minimum safety distance between the vehicles and hence reduces the accident risk. The LRR can range up to 250 m and requires a bandwidth less than 1 GHz with typical spatial resolution of 0.5 m (Ronan 2010). On the other hand, the SRR gives a wide field of view for target detection in close proximity to the car typically around 30 m. The modern vehicles are fitted with at least 10 SRRs to ensure safety aspects of the vehicle.

This chapter presents the antenna design for the SRR that requires a wideband operation for interference free target detection. Most of the antennas discussed in literature are for narrow band radar systems and hence research is conducted towards the bandwidth enhancement of the conventional narrow band array antennas. A very specific type of antenna array called Grid Array Antenna (GAA) which has gained recent research interest for automotive radar antenna development is considered in this research. The benefits of GAA, its present research status and the proposed wideband GAAs are discussed in the subsequent sections.

5.2 GRID ARRAY ANTENNAS

The GAA is a planar array antenna consisting of many grid cells formed by radiating elements and transmission lines. The GAA achieves the benefits of both conventional microstrip array antennas along with high impedance bandwidth, high gain and reduced cross-polarization. It also
includes wide angle beam scanning ability (Kraus 1964). GAAs are developed using wire or printed technology. Compared to wire technology, the microstrip printing technology enables low cost and easier production of antennas. From the time of its inception by J. D. Kraus in 1964, this antenna has not received considerable attention (Chen et al 2010). However the GAA gained attention after the advent of the microstrip version of GAA reported by Conti et al in 1981. In the past few decades, there are many useful designs of GAAs at both lower and upper frequencies for communication and sensing applications.

The utilization of GAA for narrow band automotive radar systems operating at 24 GHz frequency spectrum has gained recent research interest (Zhang et al 2011 & 2012). Recently, a few works have been reported in literature for utilization of GAA concepts on automotive radar technology. A linearly polarized microstrip GAA is proposed by Zhang et al (2011) for automotive radar sensors operating at 24 GHz frequency band. The antenna achieves a peak gain of 19 dBi with a narrow impedance bandwidth less than 1.6% centred at 24 GHz. The antenna beam width is narrow along the XZ plane and broader along the YZ plane to meet the requirements of automotive radar sensors.

Zhang et al (2011) reported a single ended and differential ended GAA to achieve 6.8% and 5.9% impedance bandwidth respectively with peak gain 13.5 dBi. A single feed GAA with 2% impedance bandwidth and 6.25% radiation bandwidth is proposed by Zhang et al (2012).

A few other GAAs reported by Nakano et al (1995, 1998 & 2002), Moheb et al (1995) and Sun et al (2009) have a small impedance bandwidth and radiation bandwidth. These antennas are reported for narrow band automotive radars. This narrow band technology suffer from severe interference effects due to many other passive sensors operating in the same
frequency band and also the co-existence of many vehicles fitted with similar short range radars (Ronan 2010). The premium car manufactures adopt wideband technology in automotive radar systems for interference mitigation and to efficiently perform collision detection and avoidance with low power consumption (Ronan 2010). Therefore the design of high gain, wideband GAA derives prime interest for automotive radar sensors.

Bandwidth enhancement of GAAs at low frequencies has been reported in literature by Chen et al 2010, Nakano et al 2013 and Feng et al 2013. Chen et al (2010) have attempted a novel configuration exploiting elliptical radiating elements to achieve simultaneously higher gain and larger bandwidth centred at 5.8 GHz. Further enhancement in gain and bandwidth is reported by exploiting elliptical radiators and sinusoidal transmission lines (Feng et al 2013). This GAA is composed of 7 radiating elements designed to operate at 2.45 GHz. The presented design achieved 25.6% impedance bandwidth (627 MHz) and 16.3% radiation bandwidth (400 MHz).

In the following sections, two bandwidth enhanced GAAs are demonstrated for application to wideband automotive radar systems. At first, bandwidth enhancement is demonstrated by reactance loading in the radiating lines of the GAA. The design of GAA constructed using radiators with high elemental bandwidth is presented in the second part of the chapter.

5.3 DESIGN OF REACTANCE LOADED MODIFIED GAA

5.3.1 Array Geometry

The concepts of microstrip GAA is extended to automotive radar sensors for the first time by Zhang et al in 2011. The GAA configuration attempted by Zhang et al (2011) has been adopted throughout this chapter and the bandwidth enhancement is demonstrated. The GAA consist of horizontal
transmission lines of width ‘w’ and vertical radiating elements of vertical height ‘l’. The ‘w’ and ‘l’ controls the impedance and frequency specifications respectively.

The narrow band behavior of the conventional GAA is due to the narrow band behavior of the microstrip straight line radiating elements. This GAA has been modified to meet the bandwidth requirements of the newly adopted automotive wideband radar. Hence, the bandwidth enhancement can be achieved by replacing the conventional narrow band radiating elements with novel unit cells that can provide wide frequency response and high gain simultaneously (Feng et al 2013). In this section, bandwidth enhancement is demonstrated using reactance loading in the radiating sections of the GAA.

The bandwidth of the radiating line is defined as the range of frequencies over which the inductive reactance cancels the capacitive reactance. To increase this frequency range over which the cancellation occurs, additional capacitive reactance is introduced to the short radiating lines through circular disc elements of diameter ‘D’. The capacitive reactance can be varied by adjusting the diameter of the circular disc. The smaller the diameter of the disc, the smaller is the realized capacitance and higher is the capacitive reactance for a given substrate material. Therefore the net reactance of the radiating lines can be varied by varying the diameter of the circular disc. This newly added capacitive reactance cancels out the inductive component for a large frequency range and hence provides an enhanced resonant bandwidth. The optimum value of ‘D’ is chosen as 4 mm to simultaneously achieve good impedance matching and desired radiation performance.

The resultant reactance loaded modified GAA is shown in Figure 5.1. The GAA has a symmetric profile and the symmetry axis lies exactly at the centre and along the y axis. The number of elements required in
the GAA is dependent on the type of radiation pattern required (Zhang et al 2012). Increasing the number of elements along the x and y axis increases the directivity along XZ and YZ plane respectively. However, for short range radar sensors, fan beam radiation pattern is desired. Hence, the number of elements along only one direction is increased. In this case, the number of elements is increased along the x axis to achieve high directivity and narrow beam width along the XZ plane. The proposed GAA consist of 33 elements in two rows each with 16 and 17 elements distributed along the x axis. Since there are only two rows along the y axis, the beam width is wider for the YZ plane pattern. This specific feature is desired as the short range automotive radars are expected to achieve lateral coverage with beam widths of at most 6° and 60° along XZ plane and YZ plane respectively (Ronan 2010).

All 33 radiating elements are connected by long transmission line which is centre fed by a 50 Ω coaxial probe. The proposed GAA uses similar radiating elements having equal length and are displaced by equal distance approximating a uniform array. The proposed modified GAA is designed on a 1.6 mm thick RO3003 substrate having a dielectric constant 3 and loss tangent 0.001 calculated at 24.5 GHz. The layout parameters of the proposed GAA and its corresponding dimensions are listed in Table 5.1.
Table 5.1  Optimized dimensions of the modified GAA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$L$</th>
<th>$W$</th>
<th>$h$</th>
<th>$w$</th>
<th>$d$</th>
<th>$D$</th>
<th>$l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (mm)</td>
<td>164</td>
<td>30</td>
<td>1.6</td>
<td>0.708</td>
<td>8.42</td>
<td>4</td>
<td>7.2</td>
</tr>
</tbody>
</table>

The radiation mechanism of the GAA can be explained using the current carried by the unloaded GAA which looks like a regular grid cells of rectangular geometry having vertical radiating sections and horizontal transmission line sections. The unloaded GAA is chosen as the loading is predominantly used to increase the operational bandwidth of the GAA. The current on the vertical radiating sections are aligned in phase and constructively interfere to produce radiation at the far-field distance. However the current in the transmission line which is separated more than a full wavelength changes phase and interfere destructively. Therefore the horizontal sections contribute only to a small radiation. Hence the GAA would produce a narrow beam along the elevation plane and a broad beam along the azimuth plane. This GAA will be located vertically in the front side of the car beneath the plastic bumper.

5.3.2  VSWR Characteristics

The modified GAA is fabricated and tested for impedance and radiation characteristics. The impedance characteristic is tested using Agilent’s E8363A PNA series Network Analyzer. The VSWR of the modified GAA is shown in Figure 5.2. The results show wideband impedance matching and hence good VSWR characteristics. The simulated and measured impedance bandwidth extends from 16.5 GHz to 28.5 GHz. However the design is carried out at 24 GHz and the bandwidth outside the defined range in Figure 5.3 show small gain and high side lobe levels along the elevation
The effective operational bandwidth is then calculated using the 1 dB gain drop bandwidth.

**Figure 5.2** VSWR characteristics of the modified GAA (Inset picture: measurement setup and fabricated prototype)

### 5.3.3 Radiation Characteristics

The radiation performance of the antenna is tested in an anechoic chamber. The measurement setup is shown in Figure 5.3. Standard gain horn antennas are used as reference to calculate the received power.

The measured XZ and YZ plane pattern is shown in Figure 5.4 and Figure 5.5 respectively. The GAA provides narrow beam width along the XZ plane and broad beam width along YZ plane. The measured HPBW at 24 GHz along the elevation (XZ) and azimuth (YZ) plane are 11° and 136° respectively. This specific feature attracts the utility of the proposed GAA for short range radars that requires large lateral coverage for target identification. The measured peak gain is 12.11 dBi at 23 GHz. The measured gain decreases with increase in the frequency. Furthermore, the HPBW increases in both the plane for frequencies below and above the design frequency.
Therefore at these frequencies, the GAA provides broad beam width along the azimuth and elevation planes.

![Figure 5.3 Radiation pattern measurement setup](image)

![Figure 5.4 Measured XZ plane pattern](image)

The comparison of the simulated and the measured gain is plotted in Figure 5.6. The effective operational bandwidth is calculated as the overlap bandwidth where VSWR is less than 2 and the gain variation is less than 1 dB.
from the measured peak gain. The measured effective operational bandwidth extends from 22.5 – 25.25 GHz which is 11.4% at 24 GHz. With 3 dB gain variation the achieved operational bandwidth is larger but the GAA exhibits severe pattern variation due to the symmetrical nature of the proposed GAA. The simulated efficiency of the proposed GAA is greater than 80%.

Figure 5.5 Measured YZ plane pattern

Figure 5.6 Gain and efficiency characteristics
5.4 DESIGN OF WIDEBAND GAA USING ASTROID RADIATORS

The conventional radiating lines in the GAA are limited by narrow band performance. Therefore in the previous section, the short radiating lines are modified to meet the required bandwidth performance. In this section, astroid like unit cells are exploited to increase the impedance bandwidth of the GAA.

The astroids are otherwise known as super ellipses that are characterized by four cusps. This specific configuration is attempted since it increases the current path in comparison with conventional straight line conductors and provides a large elemental bandwidth. Initially, GAA is developed by adopting uniform length and width of the astroid (without amplitude tapering). The side lobe levels of the proposed GAA is reduced by adopting amplitude tapering technique using variable sized radiating elements (Zhang et al 2011). In both the cases, the size of the GAA is 146 x 18 mm. The GAAs are developed on a 1.6 mm thick RO3003 substrate having a dielectric constant 3 and loss tangent 0.001 at 24.5 GHz.

5.4.1 Design of Wideband GAA without Amplitude Tapering

In the design of GAA, the dimensions of the radiating elements and the transmission lines are determined according to the frequency and impedance specifications. During the construction of the GAA, all astroid radiating elements are designed with equal vertical height $l_r$ and horizontal length $w_s$ to create resonance at 24 GHz and to meet the required impedance matching. Table 5.2 describes the dimensions of the proposed GAA. Similar to the previous case, this GAA also consist of 33 radiating elements distributed in two rows to achieve the desired fan beam radiation pattern. The GAA is excited at the centre using a coaxial probe to achieve desired
broadside radiation pattern. The GAA with uniform sized astroid radiating elements is shown in Figure 5.7.

Table 5.2  Optimized dimensions of the GAA without amplitude tapering

<table>
<thead>
<tr>
<th>Parameter (mm)</th>
<th>$L$</th>
<th>$W$</th>
<th>$h$</th>
<th>$w$</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$l_1$</th>
<th>$w_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>146</td>
<td>18</td>
<td>1.6</td>
<td>0.5</td>
<td>3.28</td>
<td>8.7</td>
<td>6.33</td>
<td>5.42</td>
</tr>
</tbody>
</table>

Figure 5.7  Geometry of the GAA with uniform sized astroid radiating elements (Black: Top radiating layer, Grey: Bottom ground layer)

5.4.2  Design of Wideband GAA with Amplitude Tapering

The amplitude tapering technique with linear amplitude variation is attempted to reduce the side lobe levels of the GAA presented in Section 5.4.1. When performing amplitude tapering, the array element with
highest excitation is located at the centre of the array. The amplitude is then decreased towards the edges of the array (Sainati 1996). The width of the radiator has control over the antenna impedance. Broader the radiator, lower is the impedance and vice versa. Hence, the centre element is designed to have the largest width \((w_{s1})\) to carry the maximum current and the width decreases at a uniform rate decreasing the current carried by the unit cell. The resultant symmetric GAA consist of unit cells with variable width from the centre along the edges of the array. This version of the GAA has a width tapering rate of 0.271 mm per unit cell with respect to the preceding unit cell from the centre of the array. The optimum tapering rate is obtained using CST Microwave Studio. The proposed amplitude-tapered GAA is shown in Figure 5.8. This linear tapering profile and the corresponding width of the radiating elements are given in Figure 5.9.

![Figure 5.8 Geometry of the amplitude-tapered GAA](image)

![Figure 5.9 Width of the astroid in a linear amplitude-tapered GAA](image)
5.4.3 VSWR Characteristics

The designed GAA is fabricated and tested for impedance and radiation characteristics. The impedance characteristic is tested using Agilent’s E8363A PNA series Network Analyzer. The VSWR characteristics of the GAA with uniform sized radiating elements and amplitude-tapered GAA is shown in Figure 5.10. The GAA without amplitude tapering provides large impedance bandwidth for a reference VSWR \( \leq 2.5 \). The amplitude-tapered GAA shows a better impedance matching than the previous version. With a reference VSWR \( \leq 2 \), the calculated impedance bandwidth is 6 GHz (21 – 27 GHz) which is 25% bandwidth calculated at 24 GHz.

![VSWR Characteristics](image)

Figure 5.10 VSWR characteristics

5.4.4 Radiation Characteristics

The radiation pattern of the GAAs is measured in anechoic chamber as shown in Figure 5.3. The measured XZ and YZ plane radiation pattern of the proposed GAA without amplitude tapering is shown in Figure 5.11 and 5.12 respectively. The measured HPBW (half power beam width) along the XZ plane and YZ plane are 10.88° and 145° respectively at
24 GHz. The peak XZ plane side lobe level (SLL) is -11 dB at \( \theta = -34^\circ \). The SLL increases for frequencies below and above 24 GHz and the measured XZ plane SLL is above -10 dB for frequencies other than 24 GHz. The antenna exhibits a wide beam-width along the YZ plane. Thus the proposed GAA can provide high lateral coverage along the azimuth plane. The peak gain is 11.59 dBi at 24 GHz. The gain-bandwidth (GBW) is calculated using 3 dB gain variation is 11.4% (22.5 – 25.25 GHz) calculated at 24 GHz.

Figure 5.11  Measured XZ plane pattern without amplitude tapering

Figure 5.12  Measured YZ plane pattern without amplitude tapering
The amplitude-tapered GAA is attempted to decrease the side lobe level. The measured radiation pattern of the amplitude tapered GAA is described in Figure 5.13 and 5.14 respectively. The HPBW of the proposed GAA is 7° and 90° along XZ plane and YZ plane respectively at 24 GHz. The XZ plane SLL is less than -16 dB which is 5 dB lesser than GAA with uniform cell size. Since, the GAA is designed for 24 GHz, SLL increases for frequencies above and below 24 GHz. The measured SLL is less than -10 dB for a large frequency range starting from 22 – 26 GHz. The measured XZ plane SLL is -11 dB at θ = 24° and -13 dB at θ = 40° for 23 GHz and 25 GHz respectively.

![Amplitude-tapered GAA pattern](image)

**Figure 5.13** Measured XZ plane pattern with amplitude tapering

Also, it can be inferred through Figure 5.11 and 5.13, the side lobes for 90° ≤ |θ| ≤ 120° are suppressed by 10 dB in comparison with the GAA with similar radiating elements. For automotive radar sensor applications, the antenna is expected to provide a HPBW beam width of at least 60° along the YZ plane for lateral coverage. This condition is satisfied by the proposed antenna thus ensuring enhanced lateral coverage of the radar system. The peak realized gain is 13.87 dBi at 24 GHz. The calculated GBW with 3 dB gain variation is 10.4% (23 – 25.5 GHz) calculated at 24 GHz. The
gain and efficiency versus frequency plot of both GAAs is presented in Figure 5.15. The simulated efficiency is greater than 80% for the GAA with and without amplitude tapered configuration.

![Figure 5.14: Measured YZ plane pattern of with amplitude tapering](image1)

**Figure 5.14** Measured YZ plane pattern of with amplitude tapering

![Figure 5.15 Gain and efficiency characteristics](image2)

**Figure 5.15** Gain and efficiency characteristics

5.5 **FEATURES OF WIDEBAND GAAs**

The features of the modified GAA and the amplitude-tapered GAA presented in Section 5.3 and 5.4 are summarized as follows,
1. Though the proposed GAAs have a medium gain than the GAAs reported by Zhang et al (2011), Moheb (1995) and Zhang et al (2011), the proposed GAAs offers larger impedance bandwidth. The reported impedance bandwidth is 1.6%, 11.2% and 0.8% for the 24 GHz GAA reported by the aforementioned researchers respectively. For short range radar communications, the realized medium gain would be sufficient.

2. The low frequency GAAs reported Chen et al (2010) and Feng et al (2013) have gain bandwidth of 400 MHz and 1.5 GHz respectively. However, for the presented reactance loaded modified GAA and amplitude-tapered design, the gain bandwidth is 2.75 and 2.5 GHz respectively. Thus the proposed solutions outperform the elliptical radiating elements in terms of both impedance and radiation characteristics. Therefore the proposed GAAs have the highest overlap bandwidth (VSWR ≤ 2 with 3 dB gain variation) compared to the GAAs reported by Zhang et al (2011), Chen et al (2010), Feng et al (2013) and Nakano et al (1998 & 2002).

3. The presented amplitude tapered 24 GHz GAA is 18% and 27% smaller than the GAAs proposed by Zhang et al (2011) and Moheb et al (1995) respectively.

4. The proposed GAAs are suited for inference reduced wideband sensing in automotive environment.

5.6 CONCLUSION

This chapter presented two versions of GAA, viz. reactance loaded modified GAA and GAA constructed using novel astroid unit cells having
high elemental bandwidth. The prototype antennas are fabricated and tested for impedance and radiation characteristics. The developed modified GAA provides 11.4% effective operational bandwidth calculated at 24 GHz with a peak gain of 12.11 dBi. On the other hand, the GAAAs constructed using astroid unit cells enhanced both the impedance and the radiation bandwidth. Results show that the amplitude-tapered GAA provides good impedance and radiation performance over the conventional GAA with uniform sized radiating elements. The presented amplitude-tapered GAA gives 25% impedance bandwidth and 10.4% radiation bandwidth. This specific GAA exhibits fan-beam radiation pattern with peak gain of 13.87 dBi at 24 GHz making the GAA suitable for wideband automotive short range radar sensors.