Application Note

Antenna Design Guide for mmWave Radar

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Abstract

The application note lists and explains the critical and salient aspects of antenna design and walks through the steps involved in designing a mmWave antenna for radar applications based on TI mmWave radar devices. The scope of this report is limited to PCB antenna designs only.

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1 Introduction

This application note guides the reader through the process of designing an antenna for mmWave radar sensor boards. Since PCB-printed patch antennas are one of the most common antenna types used for mmWave radar applications, this document focuses exclusively on that technology. Antenna-on-Package (AoP) and Launch-on-Package (LOP) designs are outside the scope of this application note.

1.1 What is a mmWave Radar Antenna?

The mmWave radar sensors are used in various applications which involve object detection and tracking using range, velocity and angle estimation. For such sensing applications the sensor uses frequency modulated continuous wave chirp signals as shown in Figure 1-1which operate at frequency bands from 57GHz to 64GHz or 76GHz to 81GHz. These chirp signals are transmitted over the scan region of interest and the chirp signals reflected back from objects and ambient are received and then used for post processing, depending on the end use case or end equipment.

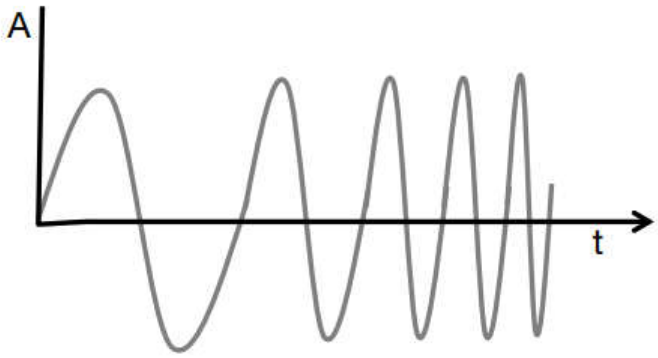


Figure 1-1. FMCW Chirp

The FMCW radar front end block diagram is shown in Figure 1-2. (1) is the Synthesizer which generates the FMCW chirp. (2) and (3) are the TX and RX antennas respectively. (4) is the mixer which takes the difference between the transmitted and received signals. Fourier transform of the IF (Intermediate frequency) signal is taken to obtain signal peaks in the frequency domain which corresponds to the range of an object. A 2D and 3D FFT further provides the velocity and angle values respectively.

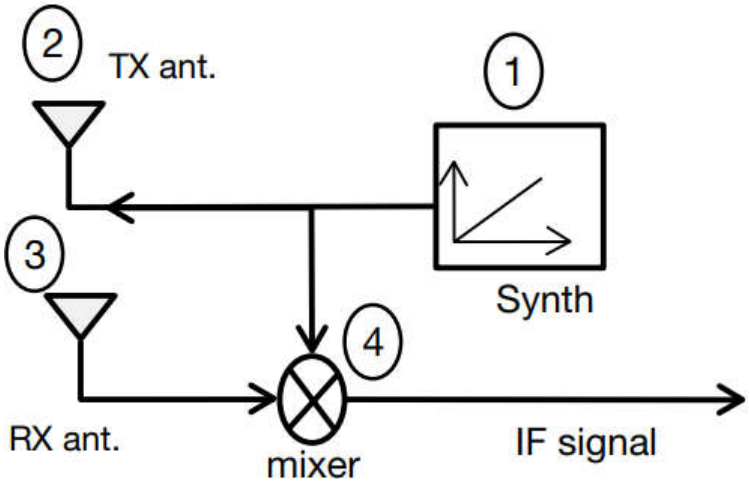


Figure 1-2. Radar RF Front End

The transmission and reception of the chirp signals is enabled by the antennas which radiate according to the specific frequency of operation. The wavelength of the chirp signals falls in the millimeter range (for example: λ for a frequency of 60GHz is 5mm), thus the name mmWave radar. The dimensions of the antennas are

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also in the millimeter range to radiate at the desired operational frequency. The mmWave radar sensor boards commonly use the PCB printed patch antennas as shown in Figure 1-3.

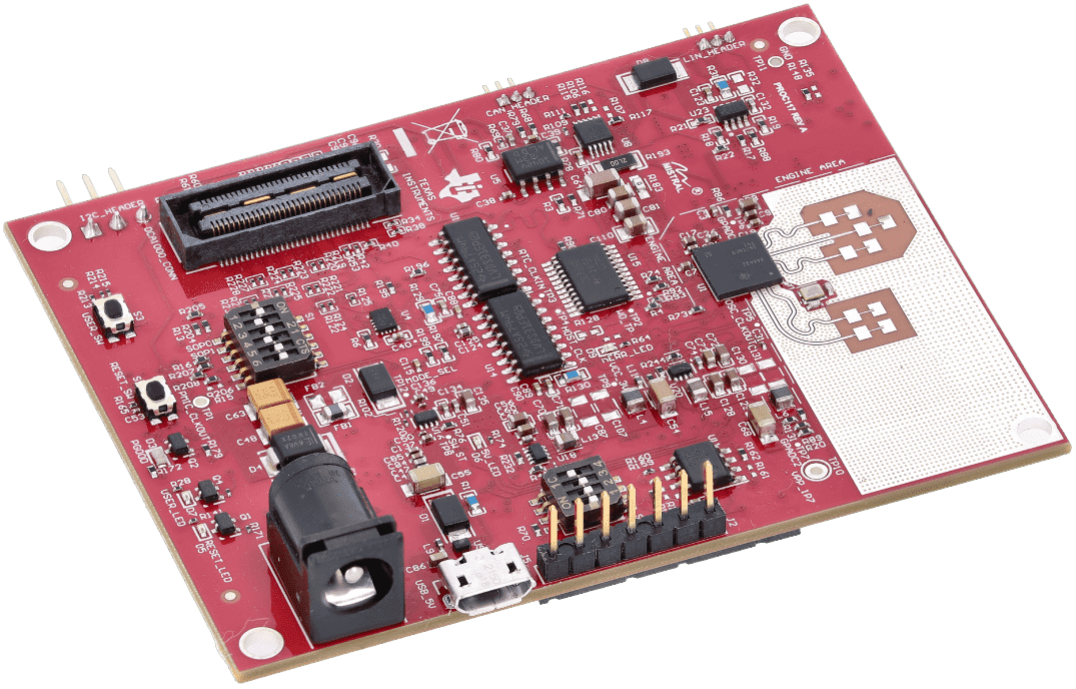


Figure 1-3. AWRL6432BOOST EVM Antenna

1.2 Features of mmWave Radar Antennas

The antenna performance is governed by certain critical parameters such as frequency of operation, bandwidth, radiation efficiency, gain and field of view (FOV). For antenna arrays, additional parameters like inter-element isolation, length matching and angle measurement are considered.

1.2.1 Fundamental Antenna Parameters

- **Frequency of operation:** The mmWave radar operates at frequency bands of 60GHz(57 to 64GHz) and 77GHz(76 to 81GHz). The frequency of operation is determined by the end application targeted. The center frequency of operation gives the wavelength which is used in designing the antennas. Any other radiation outside the frequency range is considered as unwanted emission.
- **Bandwidth:** It is that range of frequencies where less than 10% to 15% (less than -10dB to -8dB of return loss or S11) of incident power is reflected back from antennas. The S11 or the reflection coefficient gives the measure of reflected power. With higher bandwidth higher range resolution can be achieved to distinguish between close objects. This is depicted by the equation:

$$d_{res} = \frac{c}{2B} \quad (1)$$

where

  - c is the speed of light
  - B is the bandwidth

The range resolution requirements change according to the distance targeted for the application. Long range applications like ADAS 100s of meters of detection range. At such distances, the resolution requirements will be in the range of meters and thus for these applications, narrowband antennas are preferred.

Narrowband antennas operate efficiently over a small range of frequencies (usually <2GHz bandwidth) around its resonant frequency. The return loss for these antennas at the center frequency will be usually very

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low (less than -20dB S11 as shown in Figure 1-4), which offers very high-power efficiency around the center frequency and will be useful in creating high gain antennas.

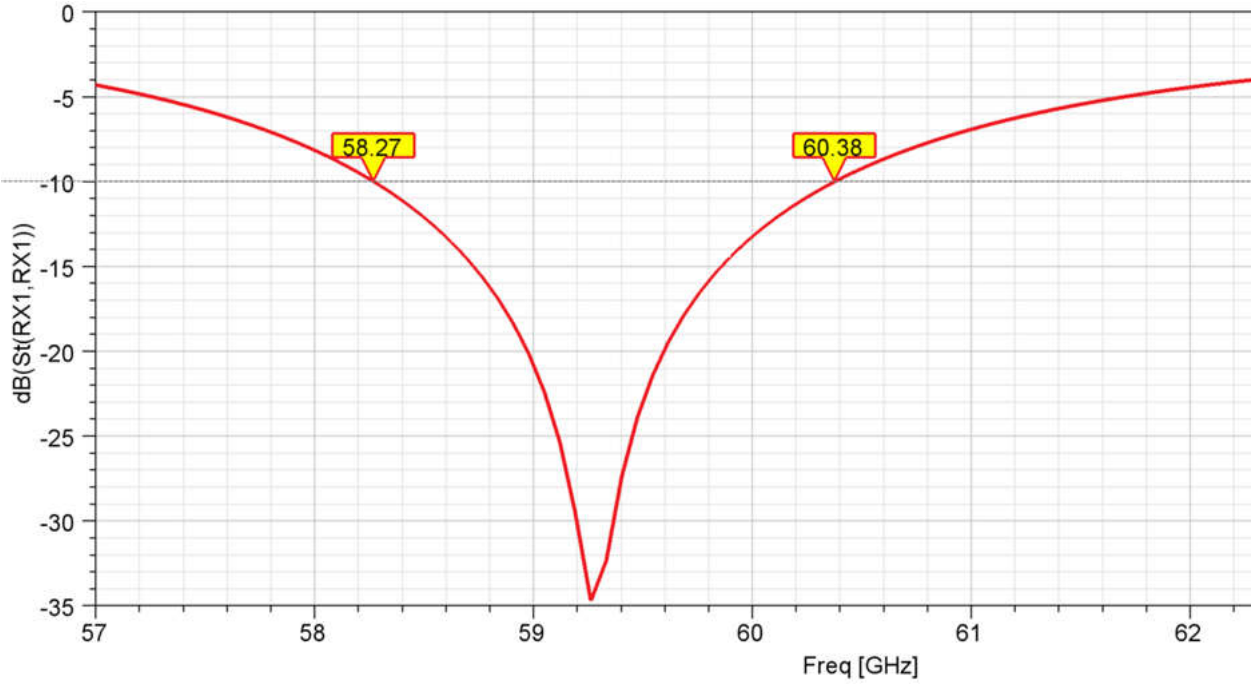


Figure 1-4. Narrowband S11

Short range applications (<30meter) such as gesture recognition requires high range resolution for detection of closely spaced objects usually in the range of centimeters. This calls for high bandiwdth or broadband antennas. Broadband antenna operates efficiently over a wide range of frequencies. Usually, the return loss will be less than -8dB to -10dB S11 (a shown in Figure 1-5) throughout the frequency range for such antennas.

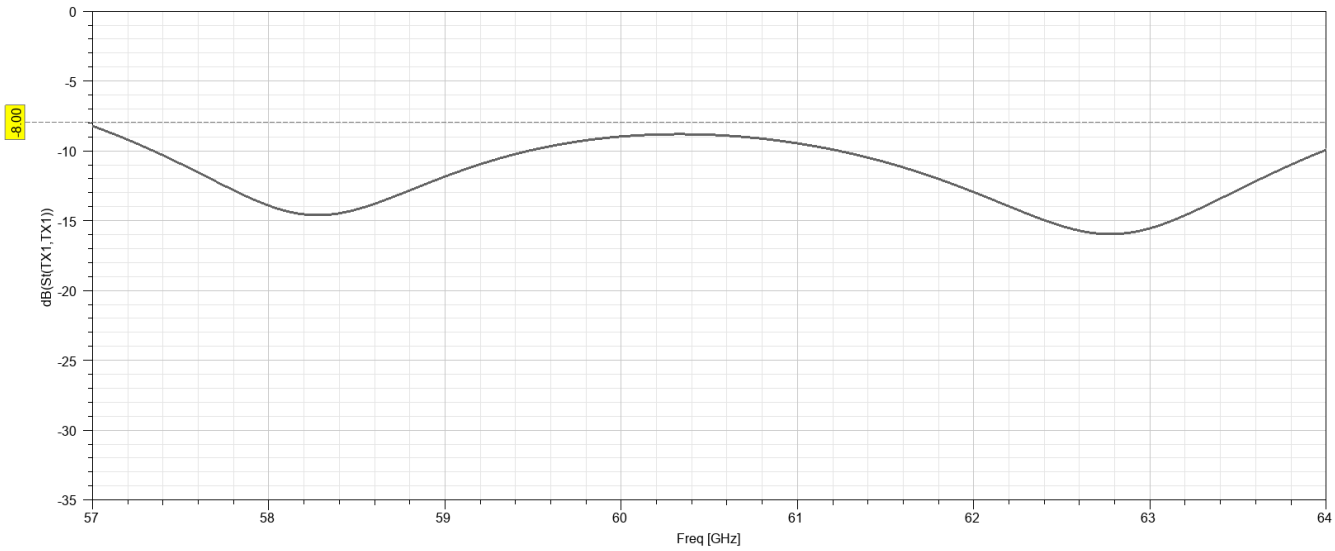


Figure 1-5. Broadband S11

- **Radiation Efficiency:** Radiation efficiency, often denoted as η, is defined as the ratio of the total power radiated by an antenna to the net power accepted by the antenna. Mathematically, it can be expressed as:

$$\eta = \frac{P_{\text{radiated}}}{P_{\text{accepted}}} \quad (2)$$

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where $P_{radiated}$ is the power emitted as electromagnetic waves, and $P_{accepted}$ is the power delivered to the antenna terminals. It is usually expressed as a percentage (0–100%) and is frequency-dependent. This shows that even a highly directive antenna will have reduced gain if its radiation efficiency is low. Several factors reduce radiation efficiency in practical antennas like conductor losses, dielectric losses, reflection losses, ground losses etc.

- **Gain:** The gain of an antenna is a measure of its directivity, representing how effectively the antenna element focuses the transmitted or received chirp signal in a specific direction relative to an isotropic radiator. It is measured in dB. A high-gain antenna concentrates power in a specific direction, whereas a low-gain antenna radiates power over a wider angular range. High gain is critical for maximizing the Signal-to-Noise Ratio (SNR), which significantly improves the detection of distant objects. For instance, a patch antenna typically achieves peak gain at the boresight (0° from the center of the radiating element). In automotive radar applications, such as front or corner radars, antennas must provide high efficiency and high gain to ensure long-range target detection. Conversely, in-cabin sensing applications require antennas with wide bandwidth and a wide FOV, prioritizing high angular and phase accuracy with moderate gain. The gain (G) of an antenna in a given direction is related to its directivity (D) and radiation efficiency by the equation:

$$G = \eta \times D \tag{3}$$

Directivity D is given by the equation:

$$D(\theta, \phi) = \frac{(4\pi \cdot I(\theta, \phi))}{P_{\text{radiated}}} \tag{4}$$

where I(θ,ϕ)) is the radiation intensity which is the power radiated from the antenna in any given direction per solid angle. θ is the azimuth angle and ϕ is the elevation angle.

- **Field of view:** It is the angular region of space over which the antenna can effectively transmit or receive electromagnetic signals according to a specified performance criterion such as gain, radiation efficiency, received power, or signal-to-noise ratio. FOV is not necessarily the same as beamwidth. Beamwidth usually refers to the angular separation between specified points on the radiation pattern, most commonly the −3 dB (half-power) points. FOV is a system/application-defined angular coverage region and may be defined using a gain or performance threshold other than −3 dB. For example, if an antenna has a requirement that its gain must remain above 0 dB, its FOV can be defined as the angular region where gain > 0dB across a reference(usually boresight) as shown in Figure 1-6 (where the FOV is ~130° at 0dB gain cut-off). Thus, an antenna could have a 60° FOV under one gain criterion and a different FOV under another criterion. FOV is measured from antenna radiation pattern plots. The antenna radiation pattern can be viewed in 2D planar plot as radiation in two directions namely azimuth and elevation. Azimuth is the horizontal direction of the signal describing left-right angular coverage and elevation is the vertical direction of the signal describing up-down angular coverage. FOV is usually expressed as the angular range in both these directions. An FOV of 120 × 80 means 120° FOV in azimuth plane and 80° FOV in elevation plane.

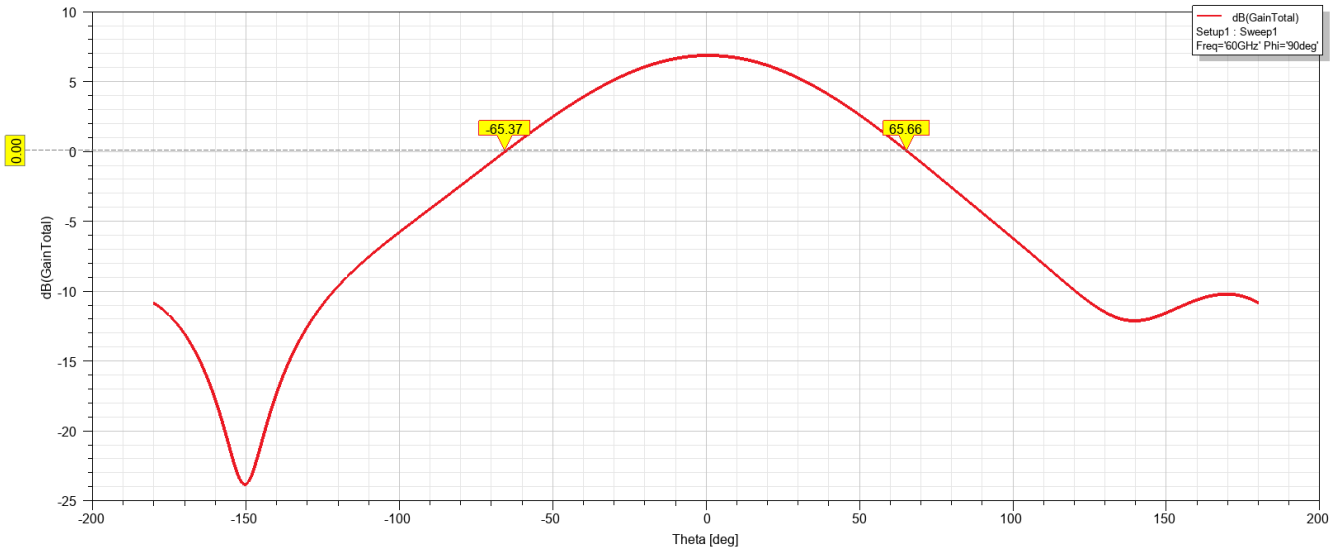


Figure 1-6. FOV

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Note

Gain and FOV exhibit an inverse relationship; increasing one typically necessitates a reduction in the other, unless accompanied by an increase in overall system efficiency.

1.2.2 Fundamental Antenna Array Parameters

- **Antenna Isolation:** Antenna isolation is an important parameter in mmWave radar systems, particularly when multiple antenna elements are integrated into the same array and are used as transmit (TX) and receive (RX) channels forming MIMO (multiple input multiple output) array. Since the antenna elements operate within the same frequency band and are physically located close to one another, electromagnetic coupling can occur between them. Insufficient isolation allows energy from one antenna element or channel to couple into another, producing unwanted interference and altering the intended antenna characteristics.

  Inter-RX isolation is the isolation between two different receive antenna elements or RX channels. Poor inter-RX isolation can introduce uncorrelated or unwanted signals between RX channels and alter the amplitude and phase relationship used for spatial processing. This can affect angle-of-arrival estimation, beamforming and spatial filtering, virtual-array response, sidelobe characteristics, target separation and detection sensitivity.

  Inter-TX isolation is the isolation between two different transmit antenna elements or TX channels. When multiple TX elements operate independently, insufficient isolation can cause energy from one TX element to couple into another TX path. This can alter the intended amplitude and phase of the transmitted signals and consequently modify the effective TX radiation pattern. Poor inter-TX isolation can therefore result in distortion of the intended TX beam pattern, changes in sidelobe levels, unwanted spatial radiation, TX-channel amplitude and phase errors, and degradation of beamforming and MIMO performance. Adequate inter-TX isolation helps maintain the intended spatial characteristics of each transmit channel.

  TX-RX isolation is the isolation between transmit and receive antenna elements or channels. This is particularly important in radar systems because the transmitted signal is intentionally much stronger than the signal reflected from a target. Even a relatively small amount of TX energy coupled directly into an RX channel can therefore create significant receiver leakage. Poor TX-RX isolation can cause TX leakage at the receiver, receiver desensitization or reduced dynamic range, increased noise-floor or interference floor, saturation or compression of the receiver in severe cases, masking of weak target echoes, reduced detection range for weak targets, false or ambiguous detections in the presence of leakage-related artifacts. TX-RX isolation is therefore especially important for maintaining the receiver's ability to detect weak reflections in the presence of a strong transmitted signal.
- **Phase Matching and Calibration of Antenna Array Elements:** In an antenna array, maintaining a known relative phase between elements is essential for accurate beamforming and angular estimation. Phase matching can be achieved through matched electrical feed-trace lengths and consistent feeding orientations. However, identical physical routing is not mandatory if the resulting phase differences are known, stable, and characterized. Feed traces can have different lengths, and elements can even be fed in opposite directions, potentially introducing a phase reversal of approximately 180°. These deterministic phase differences can be measured and compensated through antenna/radar calibration during signal processing. Thus, the key requirement is that the relative phase response between array elements is known and properly calibrated, rather than requiring identical physical feed structures.
- **Angle Estimation:** In real case scenarios of object detection across an angular field, minimum of two receiving virtual antenna elements (1TX, 2RX or 2TX, 1RX) are required for angle estimation. The angular estimation principles of MIMO arrays are discussed in MIMO Radar.

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1.3 Antenna Type Selection

Selecting an antenna involves balancing several factors: the target application, the operating frequency, the available form factor, ease of manufacture, and overall cost. The application is the starting point, because it defines what the antenna must deliver in gain, directivity, bandwidth, and FOV.

Consider a satellite communication link. It requires a highly directive antenna with high gain and a narrow FOV so that energy is focused toward a distant target. Size is a secondary concern in such systems, so physically large antennas such as Yagi-Uda, horn, and helical designs are common. These structures typically operate at lower frequencies, where their larger dimensions are practical.

mmWave applications present a different set of constraints. At these frequencies, wavelengths are only a few millimeters, and the antenna must fit within compact devices. The form factor is therefore dictated by both the application and the operating frequency. Several antenna types can be realized at this small scale, including dipoles, monopoles, and patches. The final choice depends mainly on the required radiation pattern. Dipole and monopole antennas, for example, provide omnidirectional coverage, radiating roughly equally in all directions. That is useful for general connectivity but less suited to sensing, where controlled coverage is usually needed.

Why Patch Antennas Are Preferred for mmWave Radar

Patch antennas have become the dominant choice for mmWave radar sensor boards, for several reasons.

- Design flexibility: A patch antenna can be tuned by trading bandwidth, gain, and FOV against one another. This lets designers shape the radiation pattern to suit the sensing task, whether that is wide-angle detection or long-range, focused coverage.
- Planar, low-profile form: The patch is a flat structure that integrates directly into a printed circuit board (PCB) alongside the radar chip and other circuitry. This eliminates the need for separate antenna assemblies and keeps the module compact.
- Simple enclosure: Because the antenna lies flat on the board, it can be covered with a radome (a protective cover transparent to RF energy) with little effort, which protects it without degrading performance significantly.
- Manufacturability and cost: Patch antennas are produced using standard PCB fabrication processes, so they are repeatable, scalable to high volumes, and inexpensive.

A patch antenna is built from a dielectric substrate sandwiched between two copper layers. The radiating element is formed on the top layer by etching away unwanted copper, leaving a patch of defined shape and dimensions. The bottom copper layer remains intact and serves as the reference ground plane. This design is shown in Figure 1-7

A single patch provides moderate gain with a relatively wide beam. When a radar needs longer range, multiple patches are arranged in an array. Their combined radiation increases gain and produces a more directive beam. This comes at the cost of a narrower FOV, so the array size and layout must be chosen to strike the right balance between range and coverage for the application.

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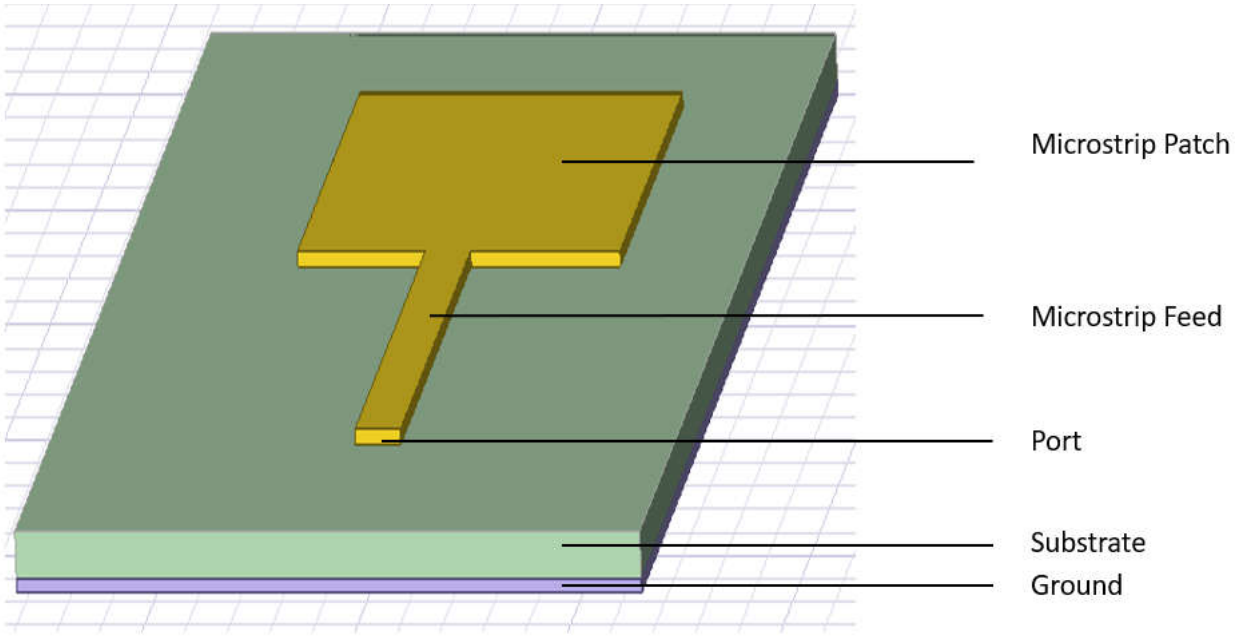


Figure 1-7. Microstrip Patch Antenna

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1.4 Critical Sections of Antenna

A basic working antenna structure can be fundamentally divided into three sections.

1.4.1 Source

In the mmWave radar sensor, RF power amplifiers (PA) on the die excite the transmitting antenna elements. The amplified chirp signals travel from the die pads through the package layers to the RF balls, then through PCB feedlines to the antenna. In reverse, the receiving antenna elements act as the source, feeding signals back to the low-noise amplifier (LNA) at the die level. The complete block diagram is shown in Figure 1-8.

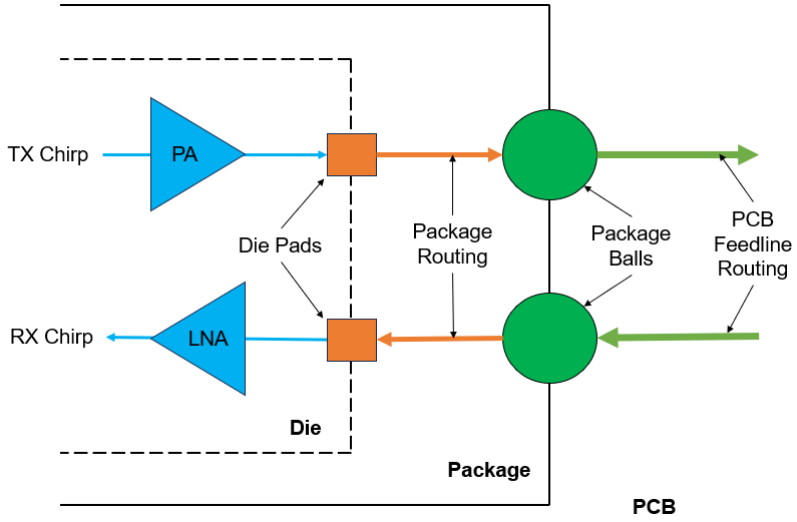


Figure 1-8. Source Block Diagram

1.4.2 Feeding Network

The feed network carries RF energy between the radar transceiver and the radiating patch, and at mmWave frequencies it is often as important to antenna performance as the patch itself. At mmWave frequencies, line losses, parasitic radiation, impedance discontinuities, and fabrication tolerances become significant fractions of a wavelength, so the feed must be designed for low loss, controlled impedance, and minimal unwanted coupling. On mmWave radar boards, the two dominant transmission-line structures are the microstrip line and the grounded coplanar waveguide (GCPW), often used together.

Microstrip Line Feed

A microstrip line, similar to the microstrip patch antenna introduced earlier, consists of a conductor strip on the top layer of a dielectric substrate with a continuous ground plane underneath as shown in Figure 1-9. It is the simplest and most widely used feed for patch antennas because it is coplanar with the patch and can be etched in the same step, with no extra layers or vias. The characteristic impedance (typically 50 Ω) is set by the strip width, substrate thickness, and dielectric constant. At mmWave frequencies, thin, low-loss substrates are commonly used, giving 50 Ω line widths of a few hundred micrometers.

Microstrip feeds have limitations at mmWave frequencies. The open structure radiates from bends, steps, and discontinuities, which raises sidelobe and cross-polarization levels. The line also couples to nearby traces and supports surface waves in the substrate. Conductor losses increase with frequency and are aggravated by copper surface roughness, since the skin depth at 77GHz is only about 0.24 µm. Because the feed line sits on the same layer as the patch, its radiation also adds directly to the antenna pattern.

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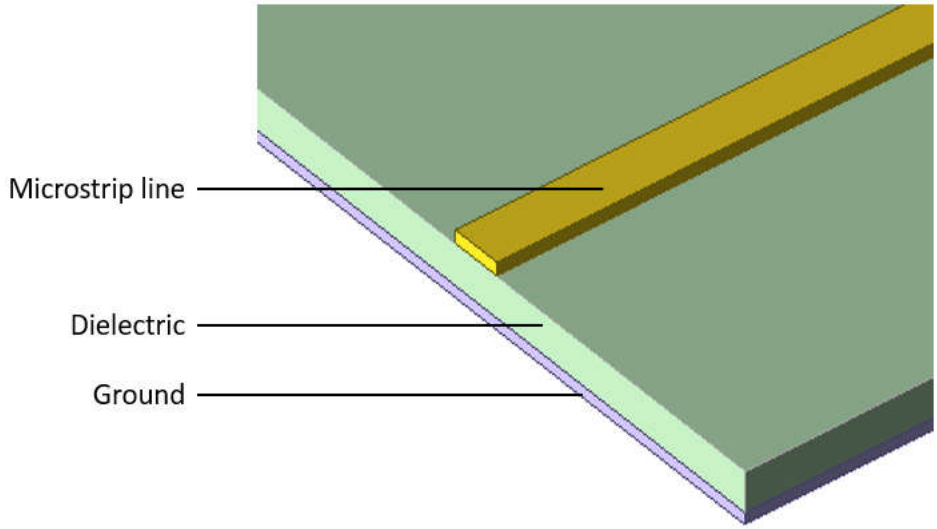


Figure 1-9. Microstrip line feed

Grounded Coplanar Waveguide (GCPW) Feed

GCPW, also called conductor-backed coplanar waveguide (CBCPW), places the signal conductor between two coplanar ground strips on the top layer, with a continuous ground plane on the bottom layer. The top grounds are stitched to the bottom ground through rows of vias, often called a via fence. The impedance is set mainly by the signal width and the gap to the coplanar grounds, so it depends less on substrate thickness than microstrip does. This gives several advantages for mmWave radar boards:

- Field confinement and isolation: The electric field is concentrated in the gaps between the signal and the coplanar grounds. With the via fence, this suppresses radiation and coupling to neighboring lines, which is important where multiple TX and RX channels are routed closely.
- Surface-wave and parallel-plate mode suppression: The via fence, with pitch kept well below $\lambda_g/4$ (often below $\lambda_g/8$), prevents surface waves and unwanted parallel-plate modes between the top and bottom grounds. λ_g is the guided wavelength along the transmission line.
- Chip and package interface: mmWave radar transceivers in BGA packages present ground-signal-ground (GSG) pad arrangements. GCPW matches this geometry naturally, giving a clean, low-inductance transition from the IC ball to the board as shown in Figure 1-10.
- Lower dispersion and tolerant geometry: GCPW maintains a more stable effective permittivity over frequency, and its impedance can be adjusted by changing the gap without significantly widening the line.

In practice, a typical radar board routes signals from the IC using GCPW and then transitions to microstrip near the antenna, since the patch itself radiates as a microstrip-type structure. This GCPW-to-microstrip transition can be made by tapering the coplanar grounds away from the signal line while keeping the impedance continuous, and placing the final ground vias carefully. A poorly designed transition causes reflections and spurious radiation, so it is usually optimized with full-wave electromagnetic simulation.

The maximum power transfer is of primary concern when connecting the source, feeding element and the radiating patch antenna structure. Thus, the impedance of the source, feed line and the radiating element is matched with each other. At the source side, the package balls sit on the PCB pads from where the feedline starts. This section is impedance matched to reduce the reflections back to the source. At the radiating side, since the input impedance at the radiating edge of a patch is high (often 150–300 Ω), a direct edge feed needs impedance matching. Common approaches include quarter wave transformer, inset feed and stub.

The trade-offs with GCPW are tighter fabrication tolerances (gap widths and via placement must be controlled precisely), higher via count and cost, and somewhat higher conductor loss than an equivalent microstrip line because of current crowding at the conductor edges.

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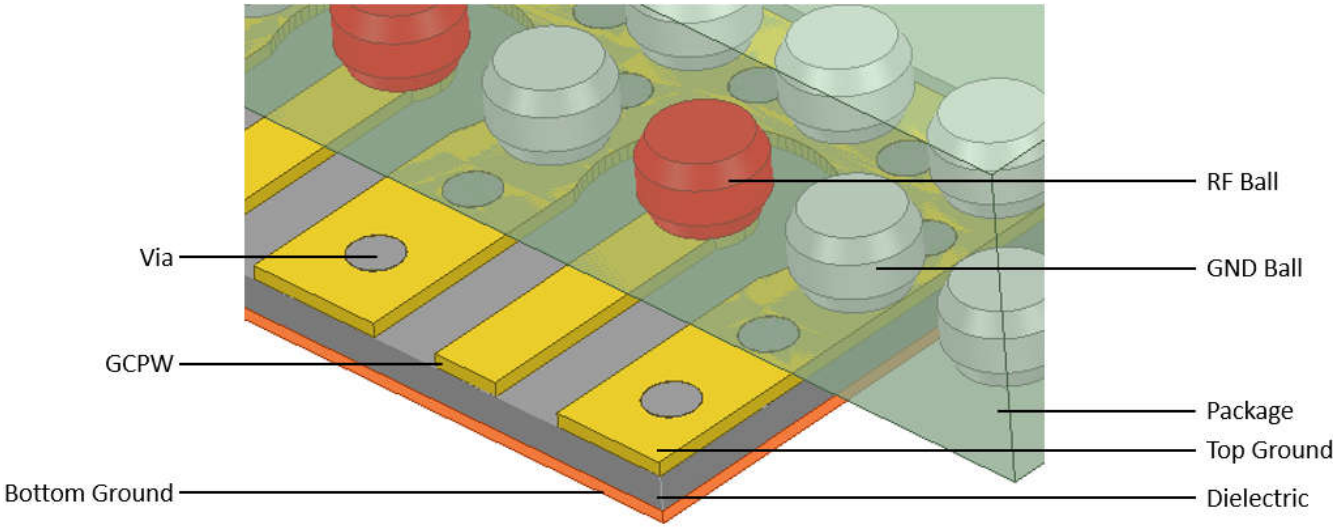


Figure 1-10. Grounded Coplanar Waveguide Feed

Alternative Antenna Feeding Techniques

- Aperture-coupled feed: The patch and the feed line are on separate substrates, divided by a ground plane containing a slot. Energy couples electromagnetically from the feed line through the slot to the patch. Because the ground plane shields the feed from the radiating layer, spurious feed radiation is very low and polarization purity is good. Each substrate can be chosen independently: a thick, low-permittivity substrate for the patch (wider bandwidth, better efficiency) and a thin, higher-permittivity one for the feed. The cost is a multilayer stack-up with precise layer alignment, and some back radiation through the slot.
- Proximity-coupled (electromagnetically coupled) feed: The feed line runs on an intermediate layer beneath the patch, with no direct contact and no slotted ground plane. Coupling is capacitive. This approach offers among the widest bandwidths of the common patch feeds and keeps the feed line away from the radiating surface. It also requires a multilayer structure and accurate alignment.

1.4.3 Radiating Element

The radiating element (commonly referred to as the antenna) is the part of an antenna that converts guided electrical signals into radiated electromagnetic waves during transmission, and converts incoming waves back into electrical signals during reception. Radiating elements take many forms, including dipoles, monopoles, helices, and patches. Patch elements are preferred in mmWave radar sensor antennas as discussed earlier.

Patches can be rectangular, circular, triangular, semicircular, or other shapes. The rectangular patch is most common because its behavior is well understood and its dimensions are straightforward to design and tune. Its resonant length is approximately half the guided wavelength ($\lambda_g/2$) at the center frequency, slightly shortened to account for fringing fields at the radiating edges. The patch width mainly influences the input impedance, bandwidth, and radiation efficiency.

To deliver maximum power to the patch, the feed impedance must match the patch input impedance at the feed point. A good match minimizes reflected power and mismatch loss, improving the antenna's overall efficiency.

The number of patches depends on the required gain and FOV. A single patch offers moderate gain with a wide beam, making it suitable for wide-FOV coverage. When higher gain and longer range are needed, multiple patches are combined into an array, which concentrates radiation into a narrower beam and reduces the FOV.

Patch array designs are of different types:

Series-Fed Patch Array

Series-fed patch array is an antenna where patch elements are connected one after the other by a single transmission line and RF power flows sequentially through each patch.

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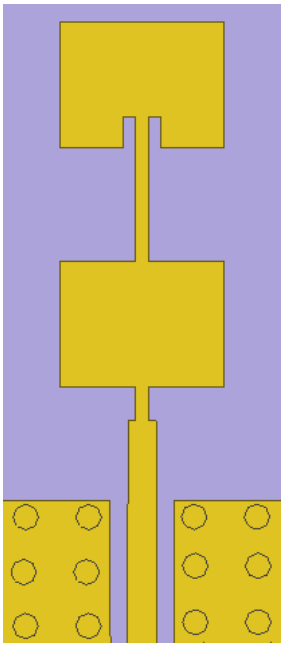


Figure 1-11. Series-Fed Patch array

Parallel-Fed Patch Array

A parallel-fed patch array (also called a corporate fed array) distributes power to all patch elements simultaneously using a power-divider network. Each patch sees the same phase and controlled amplitude.



Figure 1-12. Parallel-Fed Patch Array

Tapered Series-Fed Patch

A tapered series-fed array is a series-fed patch array in which the excitation amplitude of each element is intentionally varied to control the radiation pattern. Each patch in the array radiates different powers. This kind of design is done mainly to suppress the high sidelobes formed during normal series array design. Tapering can help the main lobe to appear cleaner than side lobes which helps in avoiding false detections.

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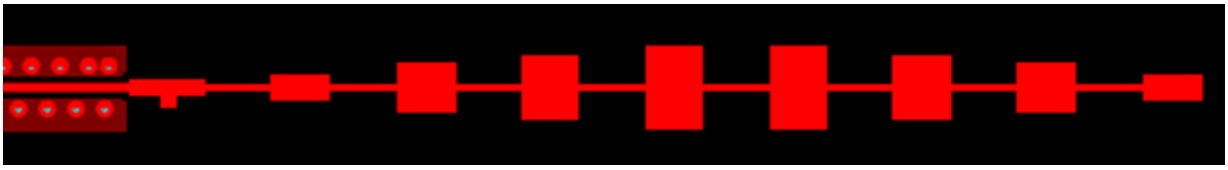


Figure 1-13. Tapered Series-Fed Patch Array

1.5 Antenna Array and Pattern Selection

A single antenna can, in principle, both transmit and receive. However, FMCW radars transmit and receive simultaneously, so sharing one antenna requires a circulator or coupler to isolate the strong transmit signal from the weak received echo. Achieving adequate isolation at mmWave frequencies is difficult, and TX leakage can saturate the receiver and raise the noise floor. mmWave radar sensors therefore use separate transmit and receive antennas, which provide better isolation and more than 1TX or 1RX also enable MIMO virtual-array processing.

Range and radial velocity can be measured with just one transmitter and one receiver. Range comes from the beat frequency of the received chirp, and velocity from the phase change across successive chirps. Angle of arrival, however, requires at least two spatially separated receive channels, because angle is estimated from the phase difference of the echo across those channels. The minimum configuration for angle estimation is therefore 1TX–2RX, or equivalently 2TX–1RX using MIMO, where the transmitters are distinguished (for example, by time-division multiplexing) to synthesize a virtual array of two channels.

Angular performance depends on the size and spacing of the virtual array (discussed in Section 1.5.1), which has M TX × N RX channels, rather than on the RX count alone.

- Resolution: A larger virtual aperture gives finer angular resolution. For a uniform linear array with λ/2 spacing, resolution at boresight is approximately 2/K radians, where K is the number of virtual channels.
- Unambiguous angle range: Element spacing determines the maximum angle that can be estimated without ambiguity. A spacing of λ/2 (based on the free-space wavelength, not λ_g) gives an unambiguous range of ±90°. Wider spacing causes grating-lobe ambiguities and a narrower unambiguous range.
- Practical FOV: The usable field of view is also limited by the radiation pattern of each antenna element, and angle accuracy degrades toward ±90° even with λ/2 spacing.

1.5.1 Virtual Antenna Array

In a MIMO radar, each TX–RX antenna pair forms one virtual receive channel. With M transmitters and N receivers, the system produces M × N virtual channels, even though only M + N physical antennas are present on the PCB. The position of each virtual element is the vector sum of its TX and RX antenna positions, measured from a common reference. This holds in the far field, where the round-trip phase of an echo depends on both the transmit and receive locations. For this to work, the signals from the different transmitters must be orthogonal at the receiver, typically by time-division multiplexing (TDM), binary phase modulation (BPM), or Doppler-division multiplexing (DDM).

Because the virtual positions depend on the physical layout, designers can place TX and RX antennas to synthesize a desired virtual geometry. A common approach places the RX antennas λ/2 apart and the TX antennas N·λ/2 apart, producing a filled uniform virtual array with λ/2 spacing. Virtual spacing is a design choice, however, not an inherent property. Sparse or non-uniform layouts are also used to enlarge the aperture, at the cost of possible ambiguities or higher sidelobes.

By this principle, 1TX–2RX and 2TX–1RX both yield two virtual channels, the minimum needed for angle estimation along one axis.

Adding TX antennas, RX antennas, or both increases the number of virtual channels and enlarges the virtual aperture. This improves angular resolution, which lets the radar separate targets at the same range and velocity but at different angles. It also improves SNR through coherent combining. Better angular separation can also result in a denser point cloud. The point cloud is formed from detections across range, Doppler, and angle bins.

Angular resolution in each plane depends on the virtual aperture along that dimension. Arranging virtual elements horizontally improves azimuth resolution, while vertical offsets enable elevation estimation. Depending

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on the application, the virtual array can be designed with more, fewer, or equal elements along azimuth and elevation. For example, automotive radars often prioritize azimuth resolution, while indoor sensing may need balanced 2D resolution.

An example of two different virtual array pattern created from 3TX × 4RX antenna array is shown in Figure 1-14

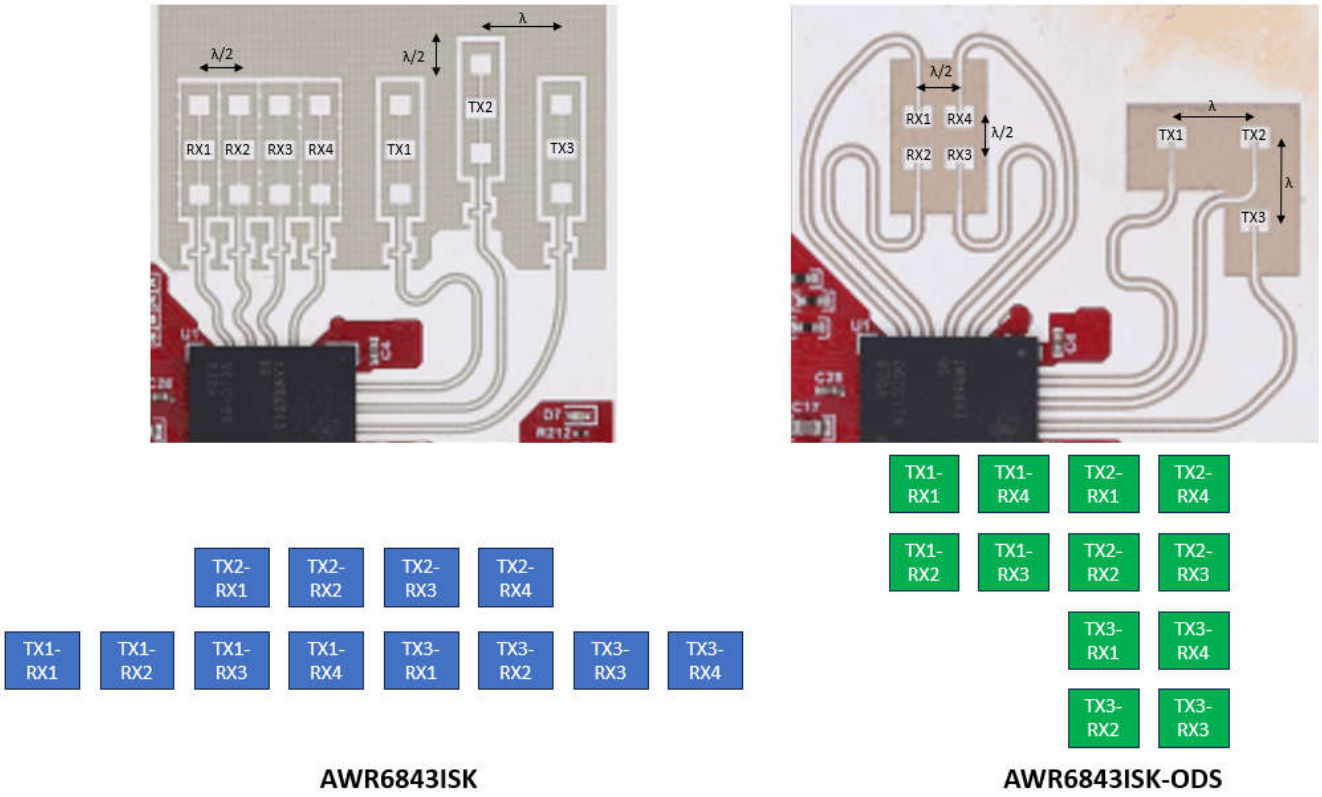


Figure 1-14. AWR6843ISK vs AWR6843ISK-ODS Virtual Antenna Array

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1.6 PCB Material Impact on Antenna Performance

A patch antenna is formed on a dielectric substrate, and the substrate's electrical, mechanical, and thermal properties shape the antenna's size, bandwidth, efficiency, and reliability. At mmWave frequencies, where wavelengths are a few millimeters and losses rise sharply, material selection is one of the most important design decisions.

Dielectric Constant (Dk)

The dielectric constant determines how strongly the substrate stores electric field energy and how slowly waves travel through it.

- Antenna size: A higher Dk shortens the guided wavelength, making the patch and feed lines smaller. A lower Dk produces larger patches and wider transmission lines.
- Bandwidth and radiation: A higher Dk confines fields more tightly beneath the patch, which reduces fringing at the radiating edges. This lowers radiation efficiency and narrows bandwidth. A lower Dk allows the fields to fringe more freely, improving radiation and bandwidth.
- Surface waves: A higher Dk and a thicker substrate encourage surface waves, which carry energy along the board instead of radiating it. Surface waves reduce efficiency, distort the radiation pattern, and increase coupling between array elements.
- Dk tolerance and stability: Because patch resonance depends directly on Dk, even small variations shift the operating frequency. A tight manufacturer tolerance (for example, ±0.04) and a stable Dk across frequency and temperature (a low thermal coefficient of Dk) are needed for repeatable performance across production batches and operating conditions.
- Design Dk vs. process Dk: Datasheets often list both. The design Dk, measured with a method closer to real circuit conditions at high frequency, should be used for simulation.
- Anisotropy and glass weave: Woven-glass laminates can have different Dk values in the in-plane and through-thickness directions, and alternating glass and resin regions cause local Dk variation. At mmWave this can lead to phase errors between array elements. Spread-glass, non-woven, or ceramic-filled PTFE materials reduce these effects.

For mmWave radar, low-Dk materials (typically 2.2–3.5) are preferred as a balance between compact size, good radiation efficiency, and manageable surface-wave excitation.

Dissipation Factor (Df or Loss Tangent, tan δ)

The loss tangent represents energy lost as heat within the dielectric. Dielectric loss increases roughly in proportion to frequency, so a material that performs well at a few gigahertz may be unacceptably lossy at 77GHz. Low-loss mmWave laminates have Df values around 0.001–0.002, compared with about 0.02 for standard FR-4, which is why FR-4 is unsuitable for the RF layers of a radar board. Lower Df improves antenna efficiency and gain and reduces feed-line attenuation.

Note that it is the loss tangent, not the dielectric constant itself, that directly causes dielectric heating.

Substrate Thickness

A thicker substrate increases bandwidth and radiation efficiency, but it also strengthens surface waves and can support higher-order modes at mmWave frequencies. A thinner substrate suppresses surface waves and makes narrow, well-controlled transmission lines possible, but it narrows bandwidth and increases conductor loss because the lines become narrower. RF layers on 77GHz radar boards are commonly around 0.127 mm (5 mil) thick as a practical compromise. Thickness tolerance matters because it affects impedance and resonant frequency.

Thermal, Mechanical, and Chemical Properties

- Coefficient of thermal expansion (CTE): A CTE in the z-axis close to that of copper protects plated vias, which are used heavily in GCPW fences and layer transitions, from cracking during thermal cycling.
- Thermal conductivity: Helps conduct heat away from the radar IC.

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- Moisture absorption: Absorbed water raises Dk and Df, so low-absorption materials maintain stable performance in humid environments.
- Chemical resistance and processability: The material must tolerate etching, plating, and cleaning chemicals. PTFE-based laminates may require special surface treatment before plating.
- Hybrid stack-ups: To control cost, many radar boards use a high-performance laminate only for the top RF layer and standard FR-4 for the inner digital and power layers. The materials must be compatible in lamination temperature, CTE, and bonding.

Copper Properties

At mmWave frequencies, current flows within a very thin layer near the conductor surface. At 77GHz, the skin depth in copper is only about 0.24µm, so the condition of the copper surface strongly affects losses.

- Surface roughness: Copper foil is roughened to bond to the dielectric, and this roughness is often several micrometers, far larger than the skin depth. Current must follow the uneven surface, effectively lengthening its path and increasing conductor loss. Roughness also raises the effective Dk, which slows wave propagation and shifts resonance. Very-low-profile (VLP), hyper-very-low-profile (HVLP), or rolled annealed copper is preferred for mmWave antennas.
- Foil type: Electrodeposited (ED) copper is common and inexpensive but typically rougher. Rolled annealed copper is smoother and lower-loss. Reverse-treated ED foil places the smooth side toward the dielectric, where most of the current flows.
- Conductivity: Copper's high conductivity minimizes resistive loss. Any lower-conductivity material in the current path, such as surface finishes or oxide layers, increases loss.
- Copper thickness and etching accuracy: Thinner copper (for example, 0.5 oz, about 18 µm) allows finer, more accurately etched features. Etching produces trapezoidal rather than rectangular conductor edges, which changes line impedance and patch dimensions slightly. These deviations become significant at mmWave, so etch compensation is used to keep features within tolerance.
- Surface finish: The finish on exposed copper affects loss because current flows near the surface. Electroless nickel immersion gold (ENIG) contains a nickel layer, which is ferromagnetic and has low conductivity, adding noticeable loss at mmWave frequencies. Immersion silver, immersion tin, and organic solderability preservative (OSP) finishes have much lower loss. Antenna regions are often left with minimal finish or treated with a low-loss option. For more details refer to TI mmWave Radar sensor RF PCB Design, Manufacturing and ValidationGuide.
- Solder mask: Solder mask over antennas and feed lines adds dielectric loss and shifts resonance, and its thickness is poorly controlled. It is typically removed from antenna and RF line areas.

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2 Antenna Design Flow

Figure 2-1 describes the steps involved in designing an antenna array for a mmWave radar sensor board.

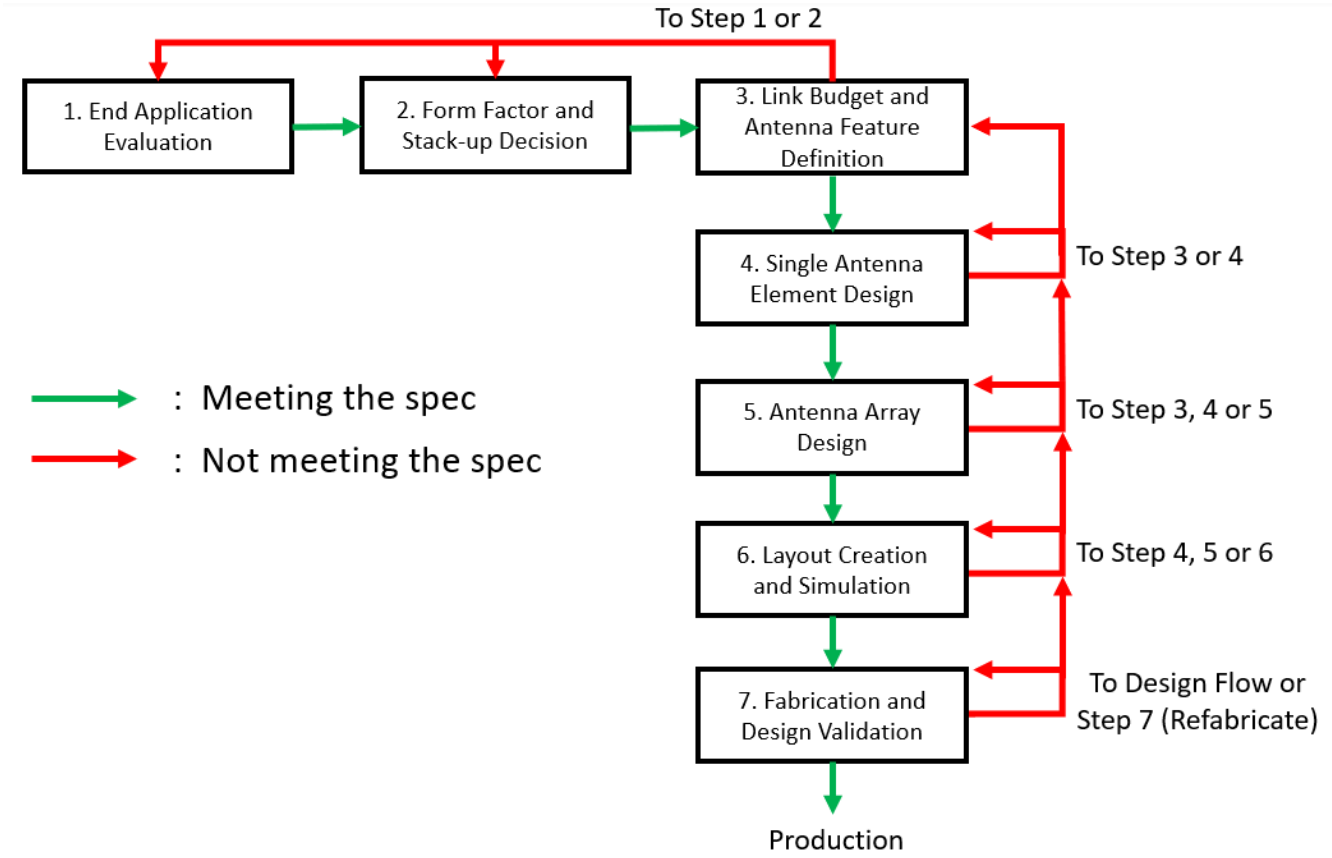


Figure 2-1. Antenna Design Flow

Note

AWRL1422 KTO Reference Design antenna is used as design example for the design flow. The EM design and simulation tool used is Ansys HFSS

2.1 End Application Evaluation

TI mmWave radar sensors are used across a wide range of end applications, including automotive and industrial systems. Each application places different demands on the antenna, so the design starts by identifying the use case and translating it into a prioritized list of antenna requirements. For example, long-range automotive radar (for example, front radar) needs high gain, a narrow beam, long detection range, and low sidelobes to separate distant targets. The FOV is relatively small. Corner and short-range radar (for example, blind-spot detection) needs a wide azimuth FOV with moderate gain, since targets are closer. In-cabin sensing needs wide FOV in both azimuth and elevation at short range, with a compact form factor. Industrial sensing (for example, people counting, presence detection, robotics, level sensing) requirements vary widely. Presence detection favors wide coverage, while level or distance sensing favors a narrow, focused beam.

From the use case, the key features are defined and ranked by priority: Gain and range, FOV in azimuth and elevation, operating band and bandwidth (for example, 60–64GHz or 76–81GHz), TX–RX isolation, form factor and sensor placement, and regulatory limits.

These features trade against each other. Higher gain narrows the FOV, wider bandwidth can reduce efficiency, and smaller size limits array aperture. Ranking them early prevents conflicting requirements later in the flow.

Cost also shapes the achievable antenna performance, mainly through the PCB material. Low-cost laminates such as standard FR-4 have a high loss tangent (about 0.02) and a higher, less stable dielectric constant.

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The high loss tangent causes dielectric loss and reduces radiation efficiency and gain. The higher dielectric constant adds to the problem by making surface waves and field confinement worse, which lowers efficiency and bandwidth. Low-loss mmWave laminates perform much better but cost more.

Designers often balance this with a hybrid stack-up, using a low-loss laminate only for the top RF layer and standard material for the remaining layers. Cost-sensitive applications may also accept reduced performance, for example by using a larger array to offset losses or settling for a shorter range.

The result of end application evaluation is a defined use case, a prioritized antenna feature list, and cost and performance limits. These feed directly into the form factor and stack-up decision (Step 2) and the link budget (Step 3).

Design Example

As a design example for the app note, consider the external automotive near field gesture recognition application like KTO (Figure 2-2). The AWRL1422 radar device is opted for this application because of the low cost and low-power capabilities the device offers since the device is expected to work on the car battery supply. The sensor module design is targeted to be of lowest cost and will majorly impact the form factor and stack-up decision. The AWRL1422 device operates in 76-81GHz frequency band with 2RX and 2TX channels. The targeted FOV for the application is 120° (azimuth) × 90° (elevation) and detection range is two to three meters.



Figure 2-2. Kick to Open

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2.2 Form Factor and Stack-up Decision

The form factor of a radar sensor board depends on the application, and it limits how much space the antennas can occupy. An automotive door-handle sensor, for example, must fit inside the handle, which sets a tight size limit. The stack-up (substrate, layer count, copper type) is decided together with the form factor, because the two together determine what antenna performance is achievable.

Impact of Form Factor on Antenna Design

- Number of elements and angular resolution: A small board limits the area for TX and RX arrays. Fewer elements mean a smaller virtual aperture, which reduces angular resolution.
- Element spacing: The RX spacing (typically λ/2) and the TX spacing needed to build the virtual array must fit within the available area. Tight space may force compromises in spacing and layout.
- Array size and gain: The antenna size and the number of patches in each array are limited, so gain is limited too. Fitting multiple patches and the feed network for higher gain becomes difficult.
- TX–RX isolation: Placing the TX and RX arrays close together increases coupling through surface waves, substrate modes, and direct radiation leakage. This raises the leakage into the receiver, which can reduce sensitivity. Isolation can be improved with via fences, ground slots, or absorber and shielding structures, and by orienting the arrays carefully, though these use additional space.
- Routing and components: The same area must hold the radar IC, feed lines, power circuitry, and connectors, so the antenna area competes with the rest of the board.
- Radome and enclosure: A tight enclosure places the radome close to the antenna, which can detune the patches, shift the pattern, and add loss. The radome thickness and distance should be considered at this stage.

Stack-up Decision

- Substrate selection: Choose the dielectric material based on the application's performance needs and cost limits (Dk, Df, thickness, stability), as discussed in Step 1.
- Layer count: More layers allow compact routing and options such as aperture or proximity coupling, but they add cost.
- Hybrid stack-up: A low-loss laminate for the top RF layer with standard FR-4 for the rest balances performance and cost.
- Copper type and surface finish: These are selected to keep conductor loss low at mmWave.
- Thickness: Substrate thickness affects bandwidth, surface waves, and the line widths needed for impedance control.
- Cost Considerations: A smaller board uses less PCB material, which reduces cost. However, a compact design may need a better laminate, more layers, or tighter fabrication tolerances to reach the required performance, which can offset those savings. The cost impact should therefore be judged for the whole design, not just the board area.
- Manufacturability: The fabrication tool limitations set limits to the minimum manufacturable dimension of copper traces and via drills. Etching tolerances and layer thickness tolerances also add up to the manufacturing variations.

Design Example

The board design is targeted for a very low form factor with dimensions 36mm x 24mm as the mounting space on the vehicle rear bumper is limited and this is a very low cost solution. The antenna design area is confined by this size.

The board layer stack-up with layer counts is shown in Table 2-1.The RF material used here is Isola FR408HR which is one of the cheapest materials available in the market. It has a Dk of approximately 3.26 and Df of approximaately 0.02 at 76-81GHz, and 5 mil thickness. The number of stack-up layers have been restricted to four to reduce the cost of PCB.

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Table 2-1. Layer Stack-up

Layer	Name	Material	Thickness	Dk
	Top Solder	Solder Resist	0.80mil	1
1	Top Layer	Copper	1.60mil	
	Dielectric 1	ISOLA FR408HR DUAL PLY, 2x1067, SPREAD GLASS	5mil	3.26
2	L2_GND	Copper	1.40mil	
	Dielectric 2	PCL370HR	45mil	4
3	L3_SIG	Copper	1.40mil	
	Dielectric 3	PCL370HR	5mil	4
4	Bottom Layer	Copper	1.60mil	
	Bottom Solder	Solder Resist	0.80mil	1

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2.3 Link Budget and Antenna Feature Definition

This step converts the application requirements into numbers: the link budget shows how much antenna gain the radar needs, and the antenna features are then defined to deliver it within the form factor from Step 2.

Link Budget

The radar equation gives the received power from a target:

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4 \cdot L} \quad (5)$$

P_t: transmit power at the IC output

G_t, G_r: TX and RX antenna gains

λ: freespace wavelength

σ: target radar cross-section (RCS), set by the target (person, vehicle, hand gesture, and so on.)

R: maximum detection range

L: system losses (feed lines, IC-to-antenna transition, radome, mismatch)

The detection SNR also depends on the receiver and the signal processing:

$$SNR = \frac{P_r}{k \cdot T \cdot B_{\mathrm{IF}} \cdot NF} \times \text{processing gain} \quad (6)$$

Noise: thermal noise ($k \cdot T \cdot B_{IF}$), the receiver noise figure (NF), and the IF bandwidth

Processing gain: coherent integration over range FFT samples, chirps, and virtual channels

The required SNR for a given detection probability and false-alarm rate is chosen first, and the budget is then worked backward to the antenna gain needed at the maximum range.

Antenna Feature Definition

The link budget results are combined with the Step 1 priorities to set the antenna specification:

- Gain: Minimum gain from the link budget.
- FOV: Azimuth and elevation coverage needed
- Operating band and bandwidth: Must cover the full chirp sweep, with margin for fabrication and temperature shifts.
- Impedance match: Return loss target (e.g., better than −10 dB across the band).
- TX–RX virtual geometry: The virtual array geometry that gives the required angular resolution and unambiguous angle range.
- TX–RX isolation: Target leakage level that does not saturate or desensitize the receiver.
- Element and array type: Single patch for wide FOV and moderate gain, series-fed or corporate-fed arrays for higher gain and narrow FOV.
- Polarization: Polarization is the orientation of the electric field vector of an electromagnetic wave as it propogates, observed over time at a fixed point. Types are linear, circular and elliptical. Typical patch antenna designs have linear polarization.

If the required gain and FOV cannot be met within the area and cost limits, the loop returns to Step 1 or Step 2 to relax requirements, change the form factor, or upgrade the stack-up.

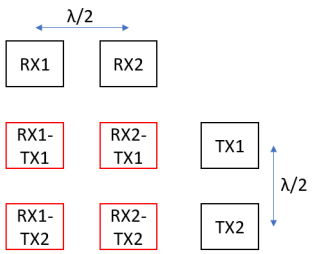
A closed link budget and a complete antenna specification becomes the targets for the antenna design.

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Design Example

The AWRL1422 reference board antenna design feature list based on the Step 1 evaluation and link budget calculations are given in Table 2-2

Table 2-2. Antenna Feature Requirements

Parameter	Required Value
Gain	> 3dB
FOV	120° × 90° at -2.5dB
Bandwidth	> 3GHz
S11	<-10dB
TX-RX Virtual Geometry	
TX-RX Coupling	<-30dB
Element and Array Type	Single Patch
Polarization	Linear

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2.4 Single Antenna Element Design

The single element combines three parts: the 50Ω feed line, the impedance matching network, and the radiating patch. The design starts at the package interface and works toward the patch. For a single patch antenna element design:

- First step is to design the feed line. For a given stack-up, the GCPW signal width and gap come from the package-to-PCB transition simulations. These account for the BGA footprint, escape routing, and via placement, and they should be used as given for the rest of the design. Now, place the via fence along the GCPW feedline ground. Use a via pitch below $\lambda_g/4$ and keep the vias close to the gap edge.
- Second step is to design the patch. The patch design equations for a given center frequency are:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{7}$$

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{\text{eff}}}} - 0.824h\left(\frac{(\varepsilon_{\text{eff}} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{\text{eff}} - 0.258)\left(\frac{W}{h} + 0.8\right)}\right) \tag{8}$$

Where,

W = width of the patch

L = length of the patch

ε_r = dielectric constant

h = height of dielectric

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\left(\frac{h}{w}\right)}}\right) \tag{9}$$

Note

The patch dimensions change with tuning and impedance matching.

- Third step is to match the patch impedance to the feedline impedance. The impedance matching network aims to increase the bandwidth and achieve minimum return loss. Inset feeding and quarter wave transformer are two common matching techniques.
  - The inset feed is designed using the equations:

$$Z_{in}(y) = Z_{\text{edge}} \cdot \cos^2\left(\frac{\pi y}{L}\right) \tag{10}$$

Where:

Z_{in} = feed line impedance

y = inset depth

L = patch length

Z_{edge} = patch edge impedance

$$Z_{\text{edge}} \approx 90 \cdot \left(\frac{\varepsilon_r^2}{\varepsilon_r - 1}\right) \cdot \left(\frac{L}{w}\right)^2 \tag{11}$$

$$y_0 = \left(\frac{L}{\pi}\right) \cdot \operatorname{acos}\left(\sqrt{\frac{Z_{\text{in}}}{Z_{\text{edge}}}}\right) \tag{12}$$

  - The quarter wave transformer(QWT) is designed using the equations:

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$$Z_0 = \sqrt{\frac{Z_{in}}{Z_L}} \quad (13)$$

Where:

Z_0 = Characteristic impedance of the QWT section

Z_{in} = Input feedline impedance

Z_L = Load impedance

The length of the transformer is $l = \lambda_g/4$

Some other impedance matching techniques also exist for microstrip patch antennas, like stub matching and tapering. Antenna designs usually have combinations of two or more matching networks to achieve desired bandwidth and return loss.

After designing the three sections, next step is to simulate the design. The simulation shows how close the calculations are to the actual EM process environment. From here, the design has to be tuned further to meet the target parameters. The tuning process begins with optimizing the impedance matching network and patch dimensions to ensure S11 meets return loss requirements across the target bandwidth. Following impedance optimization, the patch geometry is iteratively adjusted to balance gain and FOV. While increasing the patch aperture enhances gain and improves S11, it simultaneously narrows the FOV. Bandwidth enhancement can be achieved by increasing either the patch aperture or the substrate thickness; however, these adjustments necessitate a trade-off between gain, FOV, and fractional bandwidth. In this optimization workflow, the patch width is utilized as the primary tuning parameter for gain, FOV, and bandwidth, as the patch length must remain fixed to maintain the desired center operating frequency.

For single element series or parallel fed patch array design the same design steps are followed but the design equations can change.

After the single element design is finalized, the design is used for antenna array creation. If any target parameter cannot be met the requirements are relaxed in Step 3.

Design Example

The single antenna element design for AWRL1422 ref. board is shown in Figure 2-3.

The final results of the single element design are:

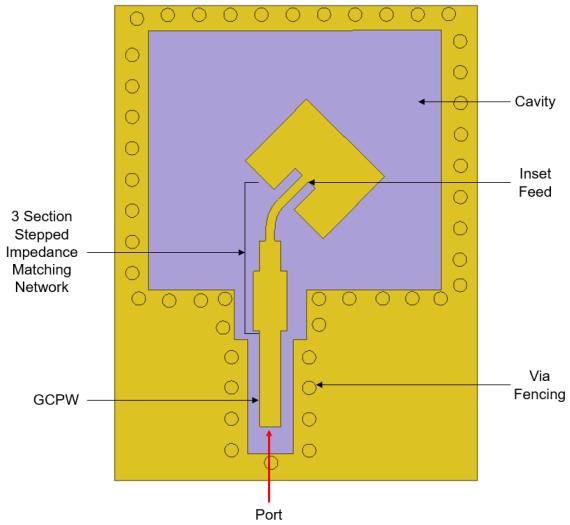


Figure 2-3. Single Antenna Element Design

- The GCPW width and air gap is fixed at 0.236mm and 0.138mm respectively through package-to-PCB simulations. The package-to-PCB transition is shown in Figure 1-10. The return loss is around -15dB for the

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76-81GHz band. The substrate Dk of 3.26 and Df of 0.02 is used for the simulation with a thickness of 5mil or 0.127mm.

- The patch is designed for a center frequency of 78.5GHz. The patch design equations give dimensions of W ≈ 1.31mm and L ≈ 1.00 mm. After EM optimization the final values are W = 1.23mm and L = 0.97mm. The patch is seen to be rotated by 45°. This is done keeping in mind the polarization alignment needed for RXs and TXs in step 6. The patch is placed in a cavity where the cavity size affects the overall radiation pattern and is optimized by EM simulations.
- The impedance matching network consists of an inset feed along with a 3-section stepped-impedance matching network, optimized by EM simulations. The 0.1mm inset feed line has ≈ 90 Ω impedance and meets the patch at this impedance point at a depth of 0.34mm. The stepped impedance network goes from 50 Ω GCPW to ≈90 Ω microstrip inset load. The 90Ω line impedance equals the load Z_L, so ideally it doesn't transform the resistance. It is a connecting and phase line, routing the feed around the 45° bend while adding some reactance tuning because Z_L isn't exactly 90Ω across the band.From the 90 Ω line a wide stepped 58Ω section connects. This is the actual impedance step between 90Ω and 50Ω. It isn't a classic quarter-wave transformer, though. A quarter-wave transformer would need √(90 × 50) ≈ 67Ω and a length of λg/4, while this section is 58 Ω and about 0.14 λg. From this section a low-Z wide section (≈40–45 Ω) connects which is further connecting to the 50Ω GCPW. This acts as a compensation and tuning section for the GCPW-to-microstrip discontinuity and broadens the bandwidth. The complete impedance matching network along with the patch is tuned together to achieve all the targeted parameters. This becomes an iterative process using the EM simulation tool. Smith chart evaluation is one of the methods to visualize and tune the impedance matching network. Smith chart provides visualization of how reflection coefficient (S11) varies with varying resistance and reactance values.All the dimensions used for the design is confirmed by the PCB fabricator to be manufacturable and the fabrication tolerance variations are also accounted for in simulations.
- Bandwidth ≈ 4GHz (76.7 to 80.8GHz at -10dB S11) at ≈ 78.5GHz center frequency.

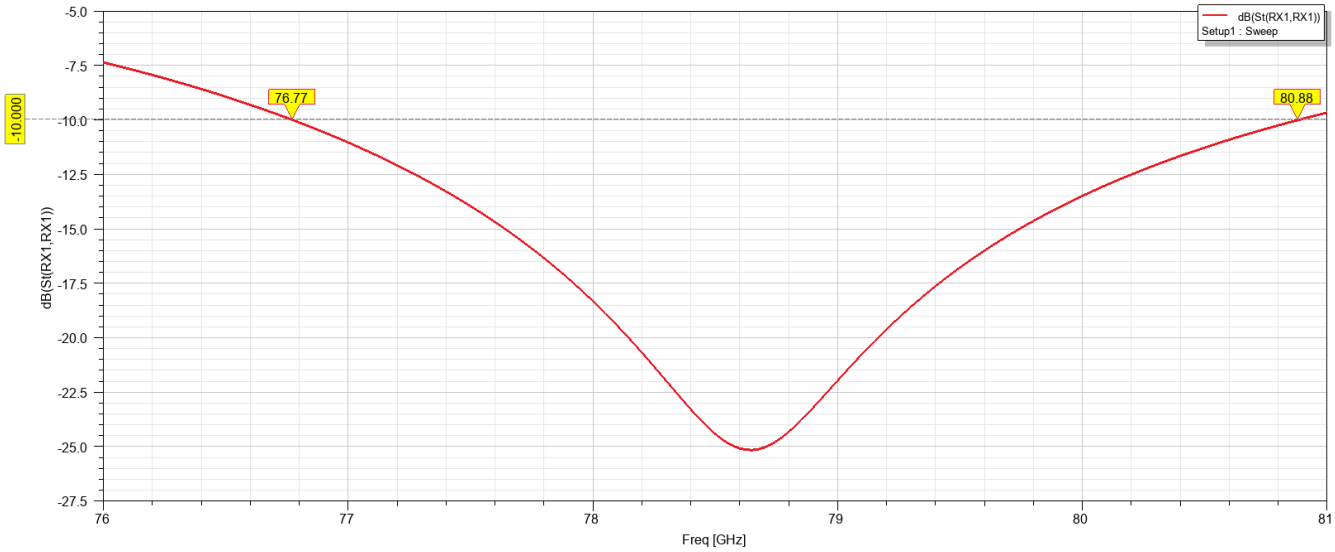


Figure 2-4. S11 and Bandwidth

- Radiation Efficiency across bandwidth corresponds to the total dielectric and conductor losses.

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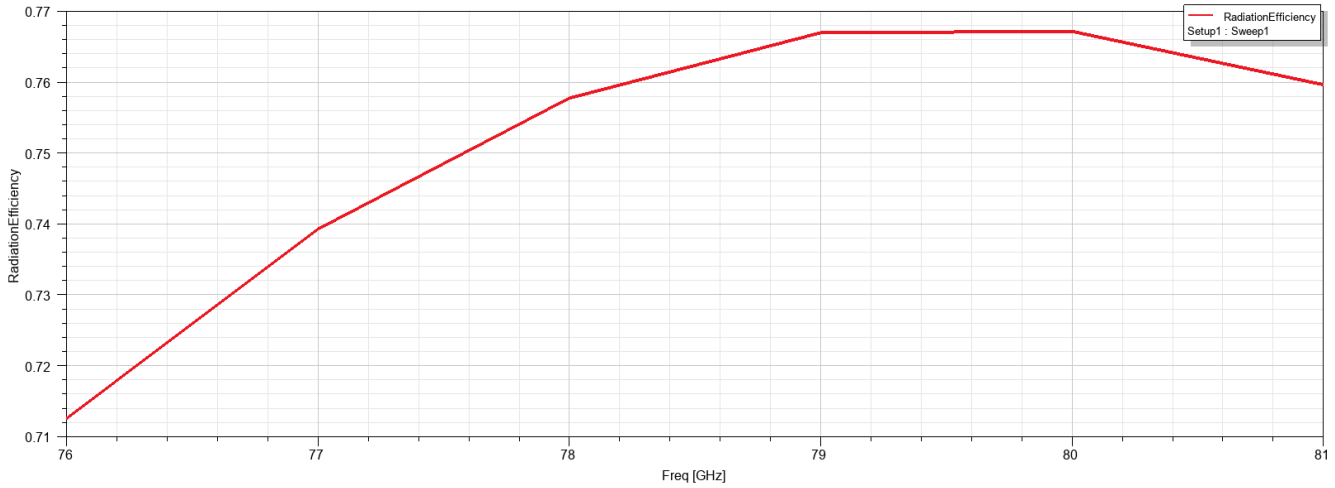


Figure 2-5. Radiation Efficiency

- Realized peak gain > 6dB across bandwidth correlates to the radiation efficiency.

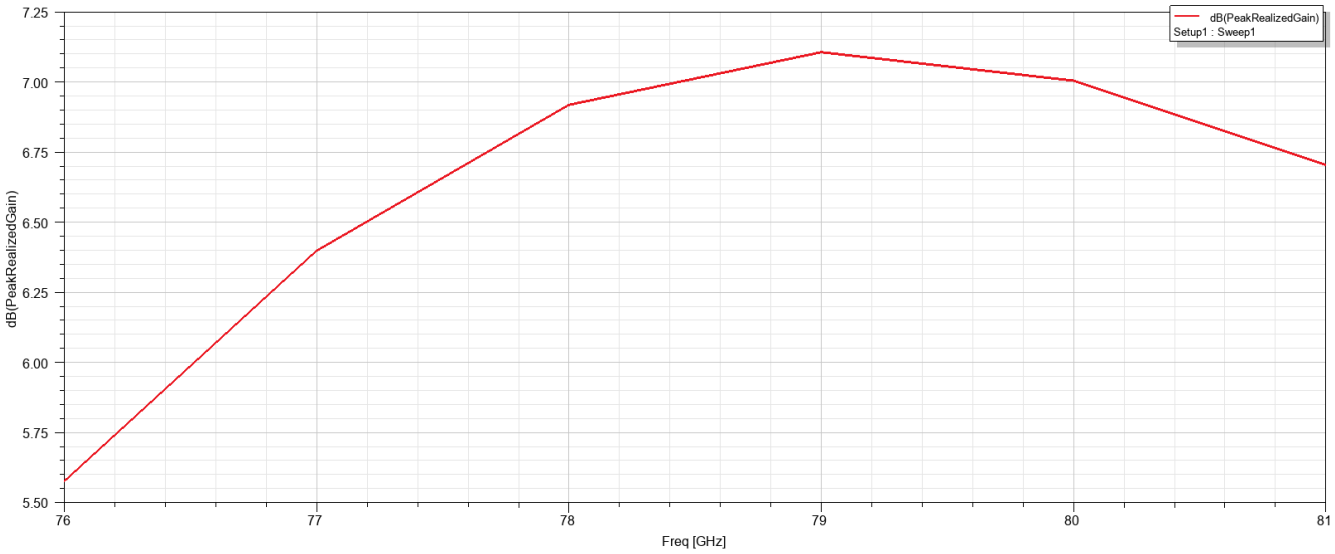


Figure 2-6. Realized Peak Gain

- FOV ≈ 135°(azimuth) x 135°(elevation) across bandwidth with a smooth radiation pattern. -2.5dB gain edge is chosen after considering least power output from device required for minimum SNR at the edge.

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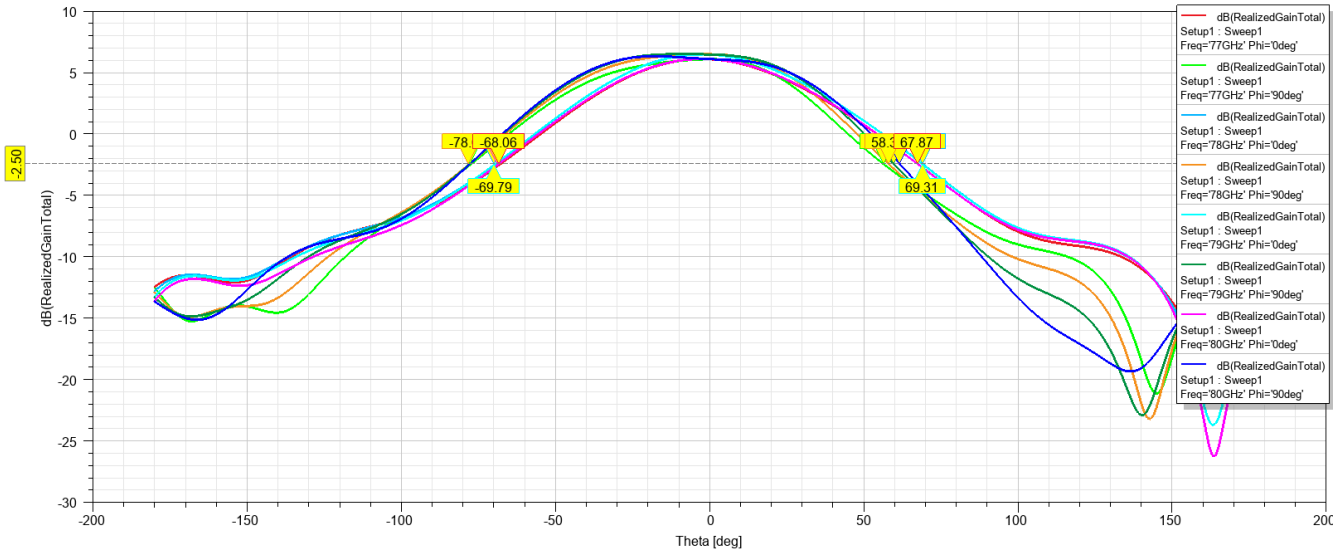


Figure 2-7. Radiation Pattern and FOV

- The 3D radiation pattern shows how the intensity of radiated lobe appears in the 3D geometry.

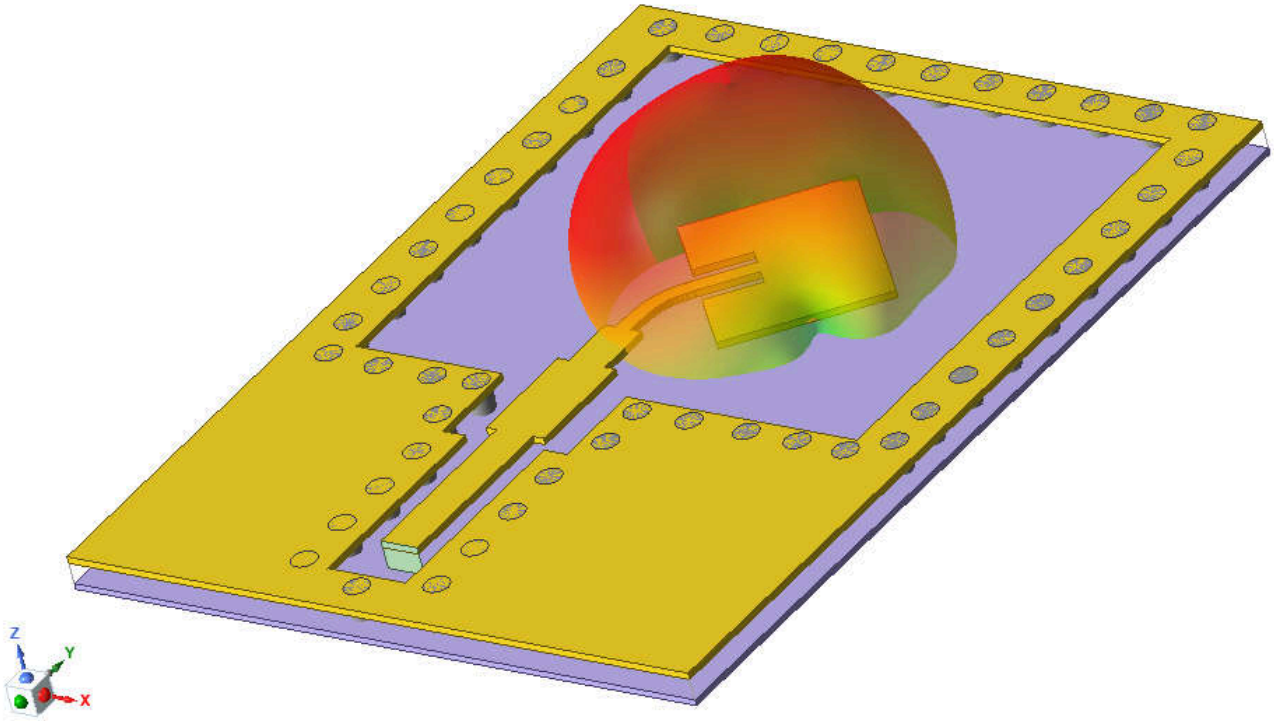


Figure 2-8. 3D Radiation Pattern

The results are meeting the target specs. So the design moves to the next step.

Note

Online microstrip line and patch calculators can be used to get dimensions for the trace and patch which can reduce the time for manual calculations.

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2.5 Antenna Array Design

The single antenna element is used to create the TX and RX antenna arrays based on the virtual antenna pattern requirement. In an array each element is influenced by the neighboring element and this changes the features of the elements. The bandwidth usually remains the same as the single element but the gain and radiation pattern(FOV) tends to change and needs further tuning. The excitation of all the elements of the array in BPM(Binary Phase Modulation) mode makes the radiation beam to constructively or destructively couple. Constructive coupling is achieved by aligning phases. It makes the beam directive and adjusting the phase of the element excitations changes the direction of the beam. Destructive coupling is achieved by opposing phases. It creates null at those specific directions. The radiation pattern from the array simulation gives these information and can be applied in real world scenarios.

The inter-element coupling numbers are also of consideration in arrays. Since the antenna element spacing is fixed from the virtual array pattern and angle estimation principles, the way to increase the isolation is to reduce the gain, FOV or reduce the element size which leads back to tuning the patch in Step 4 or re-working the target specs in Step 3. Another way is to fill the ground in between the elements with vias and also if space permits a via filled ground strip can be introduced between patches. Further, the increase in feedline length increases the trace loss which inturn increases isolation.

Design Example

The targeted array design for the required virtual array pattern is 2RX x 2TX. Since both the RX and TX array patterns are identical, the same array design is used for both.

The 2 element array design is shown in Figure 2-9. The elements are spaced at λ/2 distance where λ = 3.82mm at 78.5GHz.

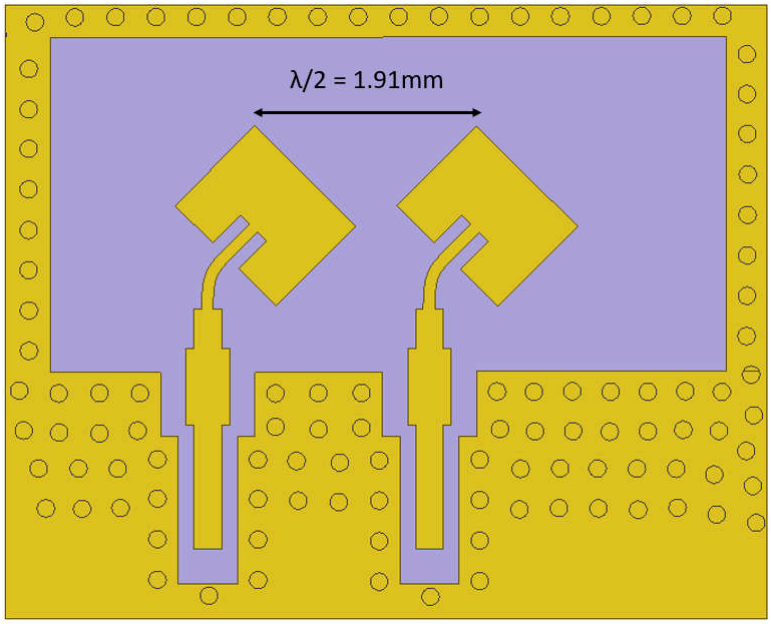


Figure 2-9. 2 Element Antenna Array

The radiation pattern of the array with different element excitation and phase configurations are shown in Figure 2-10.

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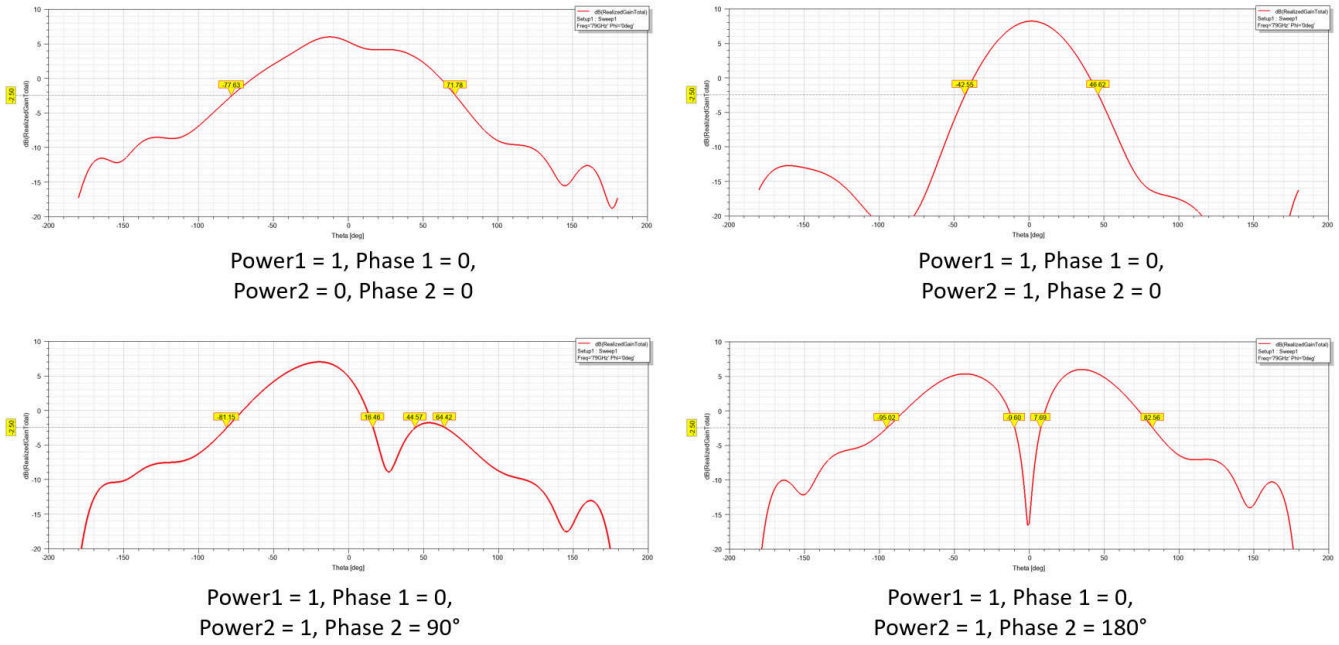


Figure 2-10. Antenna Array Radiation Patterns

The radiation pattern with single element excitation is shown first. Then the radiation pattern with simultaneous excitation of both elements with different phase values are shown. The equal phase or in-phase excitation created a directive narrow beam with higher gain at bore-sight. The 90° phase difference shifted the main lobe to a different direction whereas 180° phase difference created destructive null at the bore sight along with 2 sidelobes.

Compared to the single element, the array design results have varied but still remain within the target with; bandwidth ≈4GHz, gain > 5dBi at boresight across bandwidth and FOV ≈ 120° x 140° at -2.5dB gain cut-off. The typical inter-element isolation target for RX or TX array is around -20dB and can be relaxed depending on how much of coupling effects can be compensated by signal processing. The isolation (coupling) values across bandwidth for the array design is shown in Figure 2-11. As all the targeted specs are met, the design moves on to the next step.

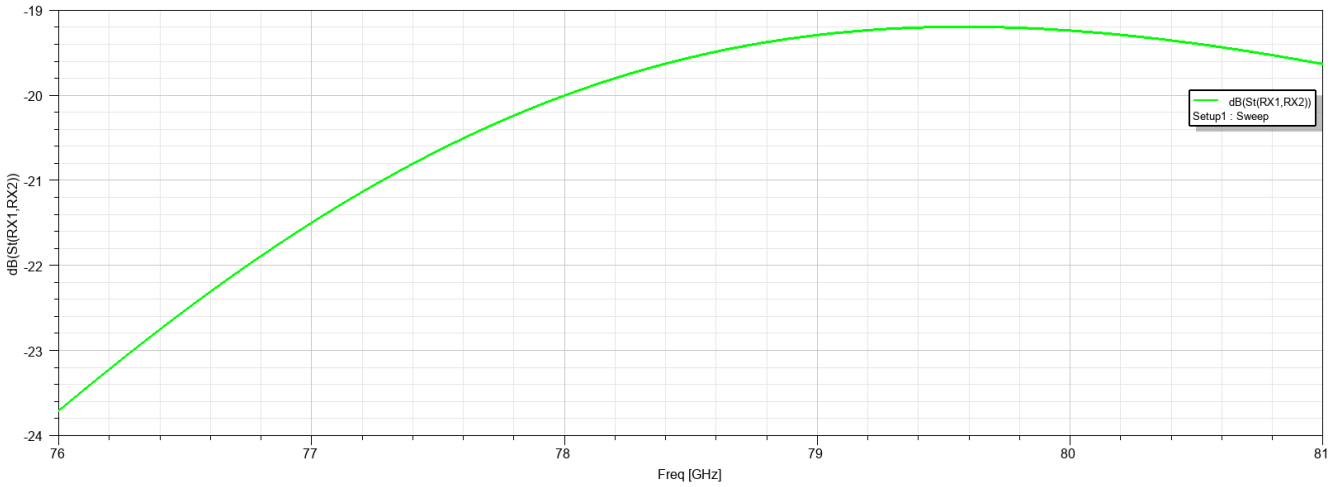


Figure 2-11. Inter-Element Isolation

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2.6 Layout Creation and Simulation

Once the antenna array design is completed, the design gets imported and integrated into the full board layout where the RX and TX arrays are placed according to the virtual array geometry and complete length matched feed traces are laid out using layout design tools. The RX and TX elements are arranged in such a way that the antenna polarization is in the same direction. The complete antenna layout is then extracted back into HFSS and simulated to get confirmation of performance. With the longer length matched traces, the results previously observed with just the patch arrays can vary. This calls for iterative re-designs of the trace layout or re-tuning of antenna till the desired results are obtained and the final design is frozen.

Note

Antenna design may require additional radome design for enclosure on the board. mmWave Radar Radome Design Guide provides the radome design steps and guidelines.

Design Example

The complete antenna layout is shown in Figure 2-12.

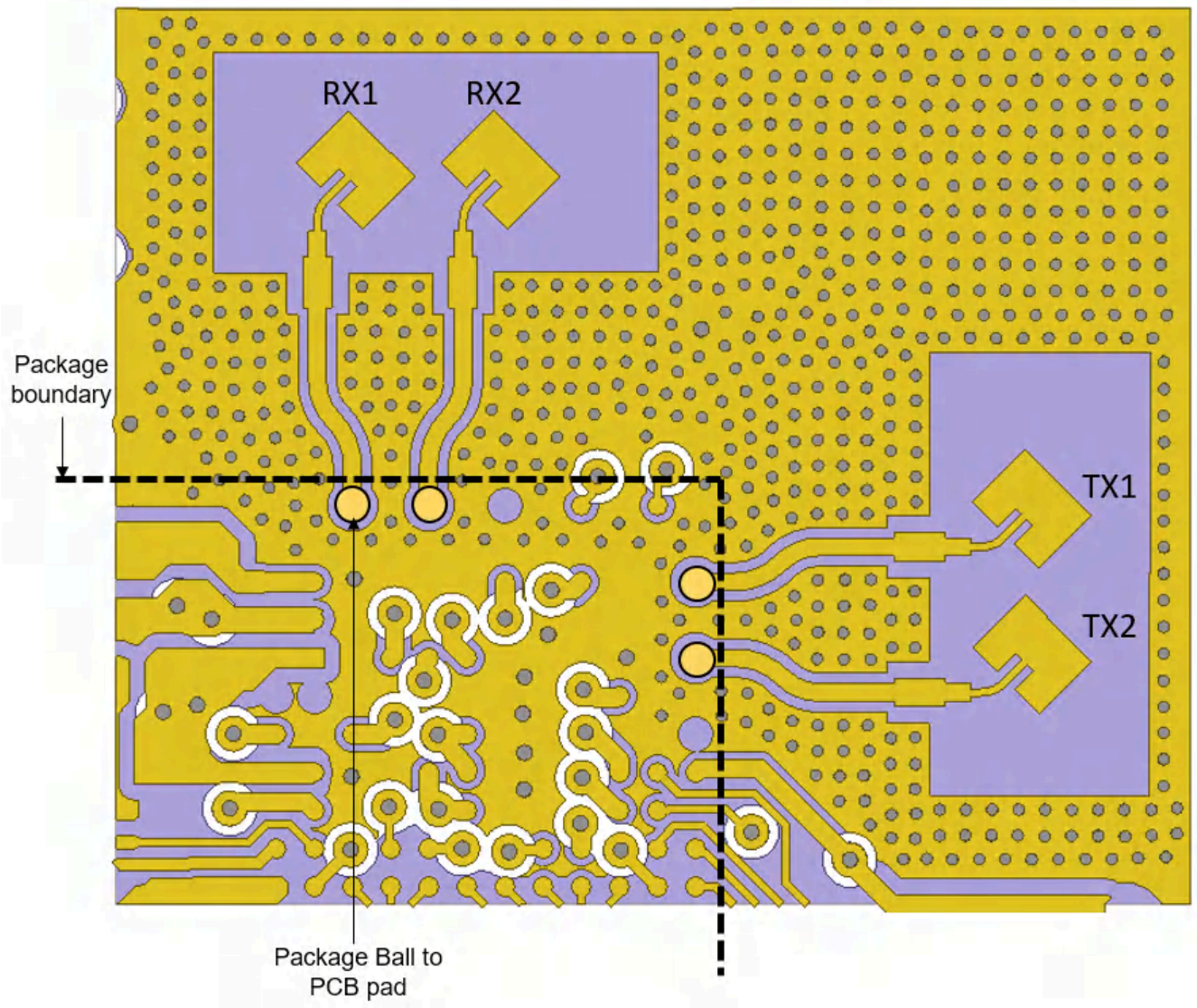


Figure 2-12. Complete Antenna Layout

Since the antenna elements are linearly polarized, it is essential that both the TX and RX elements are aligned in the same direction to become copolarized. This ensures complete reception of transmitted signals by receiver.

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The 45° tilt of the patches is helping here in a way that the same trace layout is used for both RXs and TXs which inturn helps in reducing the overall form factor of the antenna layout and thus meet overall board form factor requirements. The copper ground plane is poured with via to prevent surface currents from leaking out and exciting copper geometries comparable to half wavelength, which can act like radiators and distort the radiation pattern.

The inter RX, TX and array isolation is shown in Figure 2-13. The values are meeting the target specs of <-20dB inter-element coupling and <-30dB inter-array coupling across bandwidth.

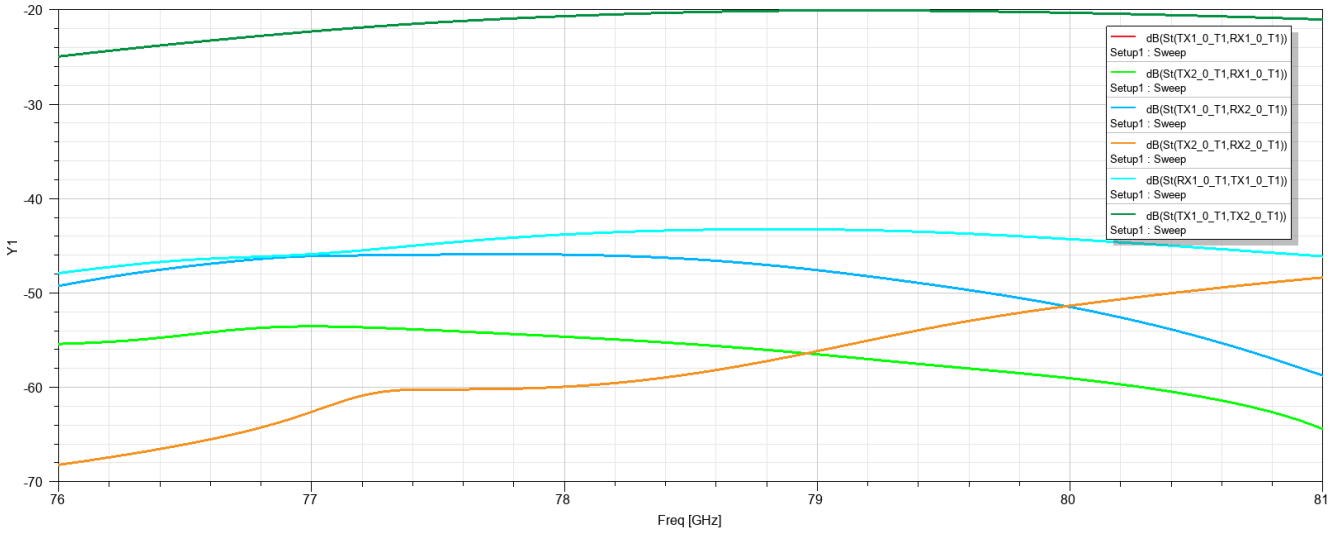


Figure 2-13. Inter-Element and Inter-Array Isolation

The bandwidth, gain, FOV and isolation targets is staying intact after tuning the complete antenna layout. Hence the complete antenna design based on the target specifications from Step 2 and Step 3 is completed. This enables the design to proceed to the next phase of board level fabrication.

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2.7 Fabrication and Design Validation

After the board layout is finalized, the layout is converted into a Gerber file or assembly file which is used by the fabrication house for board fabrication. Fabrication introduces errors in the board design which is already accounted for in the simulations by applying the known tolerance levels.

The fabricated prototype board is then validated for the antenna performance using different methods. The TX output power is measured across angles to obtain the radiation pattern of the antenna with single element and array excitations. This measurement gives a comparison against simulated radiation pattern.

Loopback measurement also known as two-way radiation measurement and post processing provide the TX-RX loopback gain, SNR and FOV of the complete TX-RX chain. Apart from TX and RX antenna gains, the loopback gain also includes the TX device power, RX signal chain gain and process gain. Both the TX output power and loopback measurements are usually conducted within closed anechoic chamber which is shown in Figure 2-14.



Figure 2-14. Anechoic Chamber

Finally, the board is used for the targeted real world application where the detection capabilities of the system is visualized using point cloud data to confirm the overall performance of the board with respect to the end application.

If there are performance issues with the manufactured board antennas, the root cause is debugged and the board is re-worked or re-fabricated. Re-fabrication can be with or without re-tuning the antenna design using the previous steps.

Once the board is validated with satisfactory performance, the design is standardized for creation or copying into more boards.

Design Example

The fabricated AWRL1422 KTO reference board design is shown in Figure 2-15.

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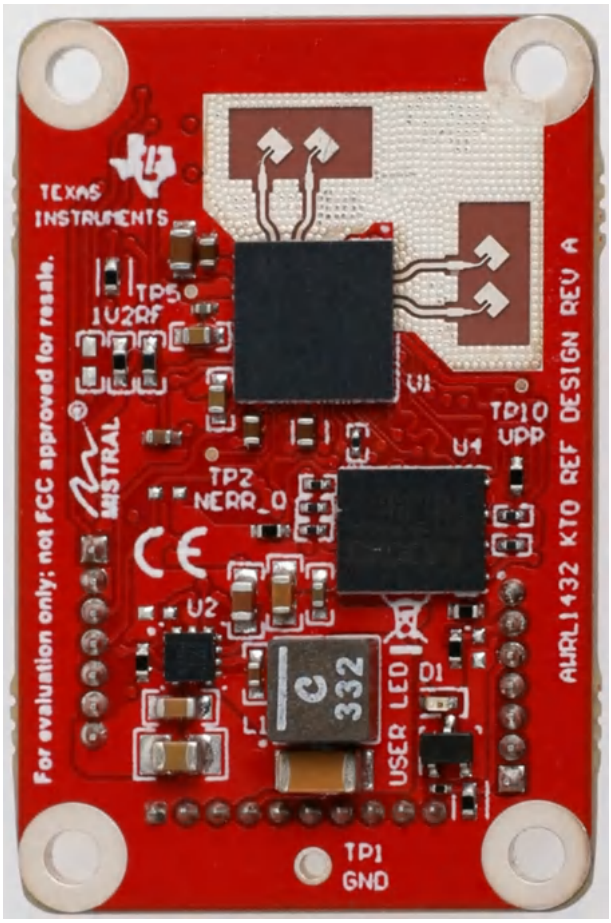


Figure 2-15. AWRL1422 KTO Reference Board

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3 Summary

Antenna design for mmWave radar is a balancing act between competing physical limits. At 60GHz and 77GHz, wavelengths are only a few millimeters, so every trace, via, copper surface and dielectric property becomes a significant fraction of a wavelength. These details directly shape how efficiently energy leaves the radar IC and where it goes. Gain, field of view, bandwidth and isolation cannot all be maximized at once. Higher gain narrows coverage, a smaller board limits aperture, and lower-cost materials add loss. The antenna is therefore not an isolated component but part of a system that includes the device, the PCB stack-up, the feed network, the virtual array geometry and the enclosure. Its success is judged by how well it serves the end application, not by any single parameter.

The way to solve this is to start from the application and work toward the hardware in a disciplined, iterative manner. First, define and prioritize what the application truly needs. Then fix the form factor and stack-up, and translate the requirements into measurable antenna targets through a link budget. Design and optimize a single element against these targets, then build it into an array that delivers the required virtual geometry and isolation. Finally, verify everything in the full board layout through EM simulation, with fabrication tolerances included. Each step feeds back to the previous ones when a target is missed, so trade-offs are resolved early, when they cost the least. Validation on fabricated hardware, through chamber measurements and real-world testing, closes the loop and confirms that the design is ready for production.

4 References

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