



Hardware and physical integration guideline PCR Sensor A111

User Guide



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A111

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1 Introduction

This document aims to provide general guidelines for the hardware and physical integration of the Acconeer A111 radar sensor. The A111 sensor is a fully integrated 60 GHz radar including the transmitter and receiver antenna. The Tx/Rx antenna is a folded-dipole type and the E-plane and H-plane of the antennas are indicated in Figure 1. The radiation pattern of the radar transceiver can be found in the A111 datasheet [1]

The provided guidelines aim to optimize the radar sensor performance when integrating it into your host product.

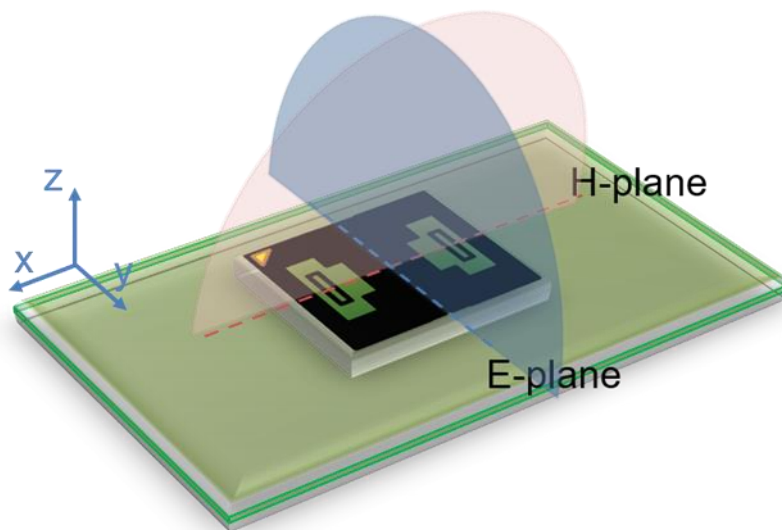


Figure 1 Sensor mounted on a printed circuit board (PCB). E-plane and H-plane are highlighted with blue and red color, respectively.

1.1 Radar loop equation

Consider a signal transmitted through free space to a radar target located at distance R from the radar. Assume there are no obstructions between the radar and the radar target, and the signal propagates along a straight line between the two. The channel model associated with this transmission is called a line-of-sight (LOS) channel. For the LOS channel, the corresponding received reflected power from a radar target, i.e. the signal to noise ratio (SNR), can be defined as

$$SNR = C\sigma\gamma \frac{1}{R^4}$$

R is the distance of the radar to the target, C is the radar loop gain, including both the transmitter and receiver chain (two-ways signal path), σ is the Radar Cross Section (RCS) of the scattering object and γ determines the reflected power of the object's material. RCS depends on the roughness, size and shape of the scattering object. Moreover, SNR depends on the sensor profile setting. A comprehensive explanation of the sensor profiles can be found in Acconeer's "Radar Sensor Introduction" [2].



1.2 Radar radiation pattern

When characterizing the gain, we refer to the radar loop gain defined in the radar equation section. Figure 2 shows the radar setup configuration for the radar radiation pattern measurement. The reflector which in this case is circular trihedral corner (radius of 5 cm) is located at the far-field distance from the sensor (1 m). The far-field distance can be determined by the aperture of the sensor and the radar target.

$$R_{farfield} > \frac{2A^2}{\lambda}$$

where A is the largest dimension of either the sensor or the radar target. Envelope service can be used to collect the reflected power at the fix distance from the radar target at different rotation angle.

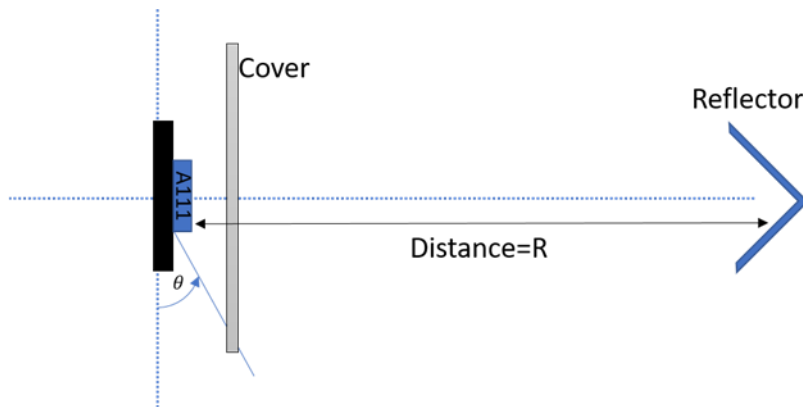


Figure 2 Measurement setup for sensor radiation pattern.



2 HW Integration - Schematics

2.1 Power

The A111 is powered by 1.8V and all the control signals and the SPI interface are 1.8V pins. It must therefore be ensured that all host MCU pins connected to the A111 are at 1.8V. If this is not the case, level-shifters must be used in between the A111 and the host MCU.

As mentioned in the power consumption summary of the A111 datasheet, the A111 consumes typically 66uA when the ENABLE pin is set low. If the leakage current is to be even further reduced, the power to the A111 must be switched off. It can be achieved either by using a low-leakage power regulator with an enable/disable function (if 1.8V is not available in the system) or a low-leakage power switch in between the two 1.8V domains. In both cases, a control signal, PMU_ENABLE, is needed. See Figure 3 for details.

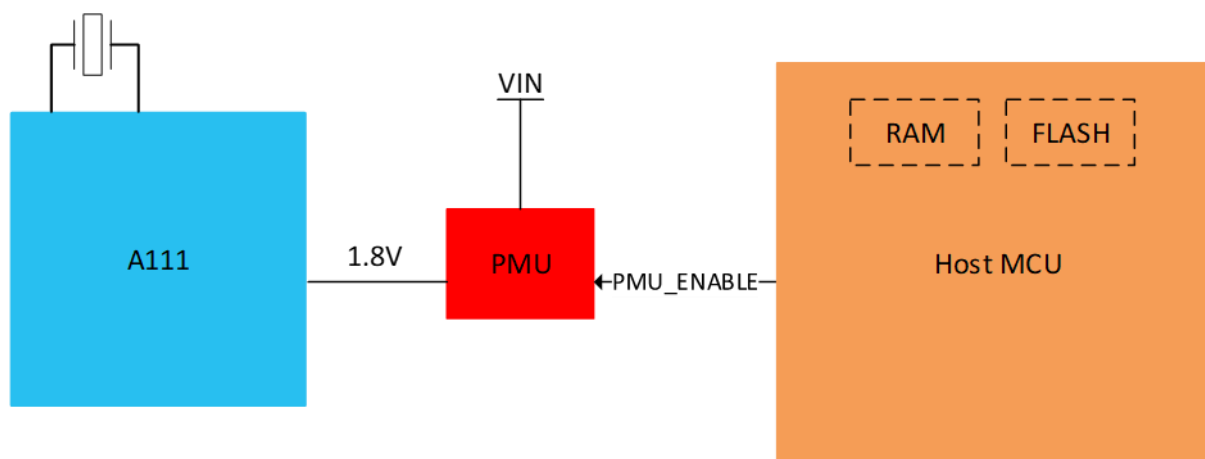


Figure 3 Block diagram of how to connect a Power Management Unit for controlling the 1.8V to the A111.

If the power to the A111 is switched off in between sweeps it is important that the control signals and SPI interface are pulled low during this time, otherwise reverse leakage will occur via the ESD diodes in the A111. If it is not possible to set the SPI interface in such a state (either via SW or by configuring any level-shifters that might be used in the design), the problem can be solved by adding a power switch only to VIO1 and VIO2. This way the leakage will be significantly lower than 66uA, but the control signals and SPI interface of A111 will still be supplied by 1.8V and thus no reverse leakage will occur. See Figure 4 for details. The Acconeer High Performance Module shows how to integrate a power switch into the design, refer to the XM112 datasheet [3].

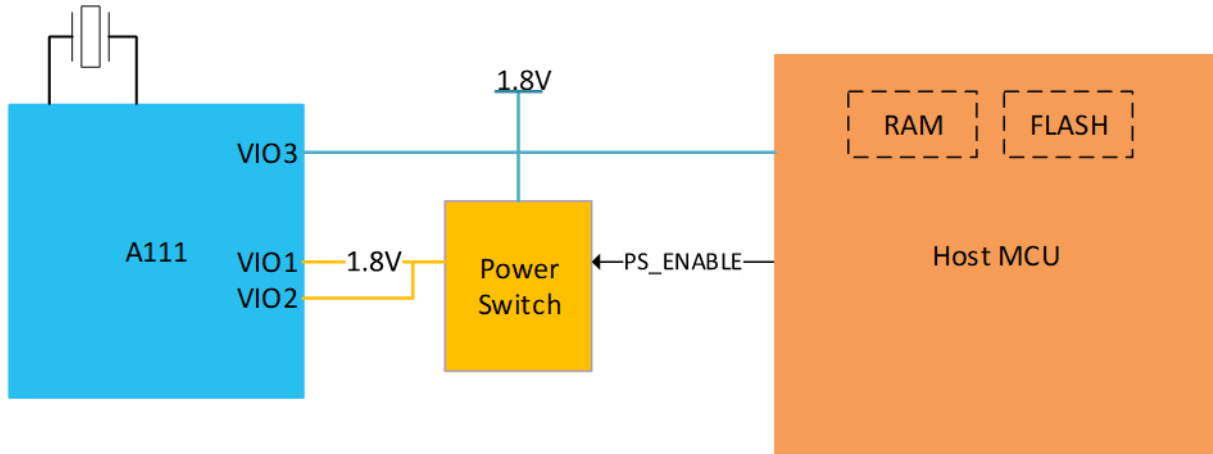


Figure 4 An example of how to connect a power switch to reduce the leakage current when A111 is powered off.

2.2 SPI Interface

To optimize the performance and speed of the SPI interface, the A111 and the MCU should be placed on the same PCB. If it is necessary to route the SPI interface via a cable, it is recommended that differential routing is done for SPI_CLK, SPI_MOSI and SPI_MISO. This is enabled by using a differential driver circuit as described in the XC122/XR122 EVK HW User Guide [4]. An example is shown in Figure 5.

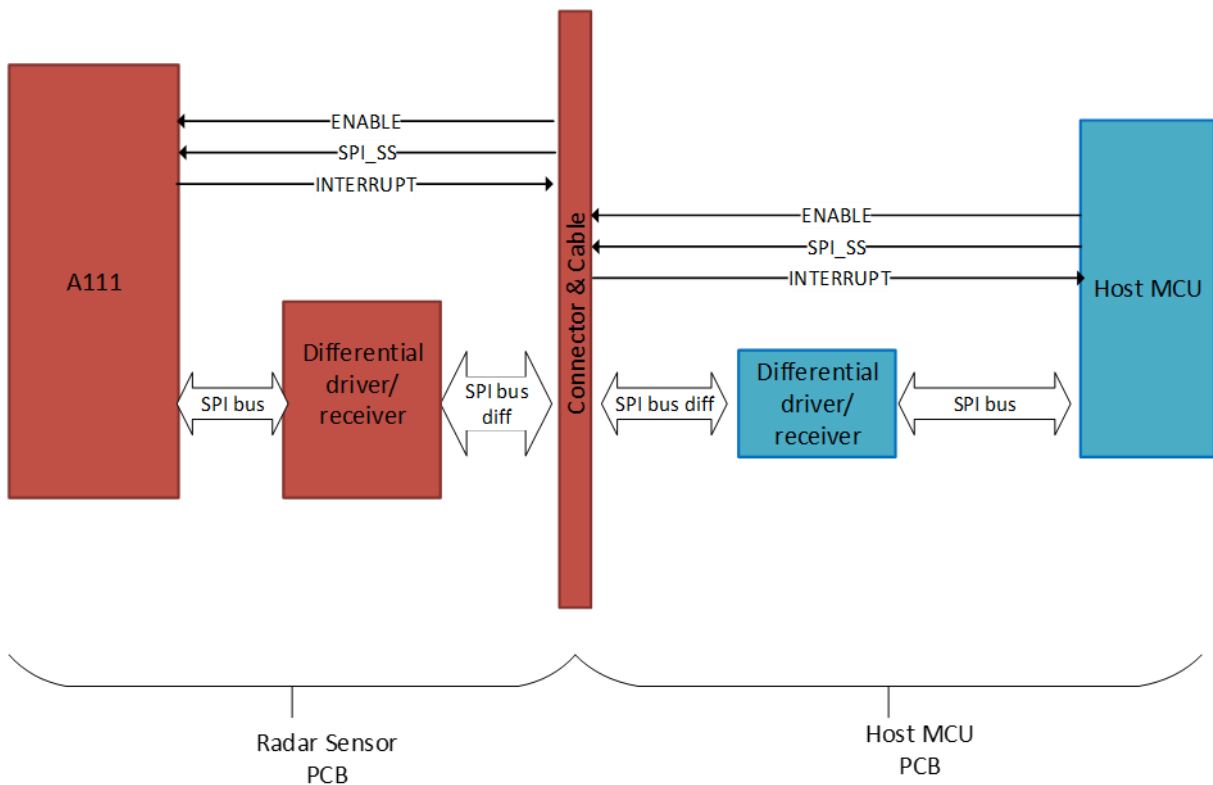


Figure 5 An example of how to use differential driver circuit if the SPI interface between A111 and Host MCU is routed via cable.



3 HW Integration - PCB

This chapter describes means of optimizing the sensor performance by properly designing the printed circuit board (PCB).

3.1 Sensor ground plane

To optimize the sensor transceiver gain, the sensor must be shielded by a solid ground plane. The area of the ground plane relates to the sensor transceiver gain as shown in Figure 6. It is recommended to place the sensor at the center of the PCB to avoid any tilt on the main radiation beam of the antennas.

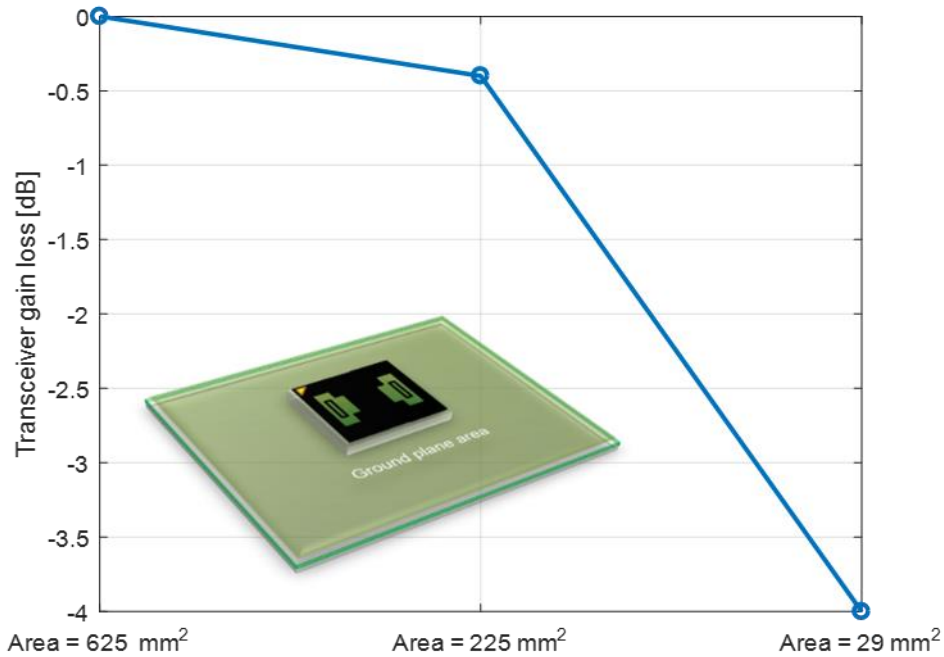


Figure 6 Simulated relative transceiver gain loss as a function of extended board ground plane area. The area is quadratic.

In terms of regulatory compliance, any holes in the ground shield must be significantly smaller than the wavelength of the radiation that is being blocked (5 mm for the A111 sensor), to effectively approximate an unbroken conducting surface.

For manufacturing reasons, it is recommended to not flood the ground area in between the A111 ground balls. It is recommended to connect the ground balls of A111 with individual traces. It is very important to connect the ground below A111 to the Main ground plane surrounding the A111. An example of how to properly connect the sensor ground plane is shown in Figure 7.

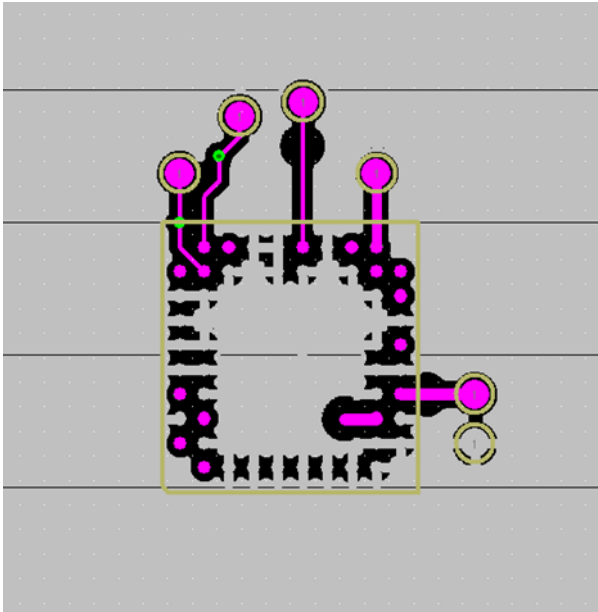


Figure 7 An example of a properly connected ground plane below the A111 radar sensor.

3.2 Sensor underfill

Underfills are usually made of materials which are characterized by their dielectric properties. The sensor underfill material should be chosen to have as low dielectric constant and loss tangent as possible. Dielectric constant determines the reflectivity of the medium and loss tangent indicates the dissipation effect of the material and both are frequency dependent.

3.3 Integration with other components

It is optimal to have no electronic components on the same side of the PCB as the sensor is located. The electronic components located on the same side of the PCB as the sensor will cause the EM waves to be scattered. The component size, shape and material determine the amount of scattered energy from the component. If it is necessary to locate a component on the same side as the sensor, the distance between the sensor and the component must be taken into consideration.

Figure 8 illustrates different strategies for placing a component close to the sensor. This is important to consider when detection range is set to close-range (distances < 150 mm), as reflections from the components can cause coherent or non-coherent interference. It is recommended to place the object in the green areas as highlighted in Figure 8. The highlighted yellow area is more sensitive to the placement



of an object. Optimum distance depends on the material, shape, size and orientation of the object. Moreover, the height of the object should not exceed the sensor's height.

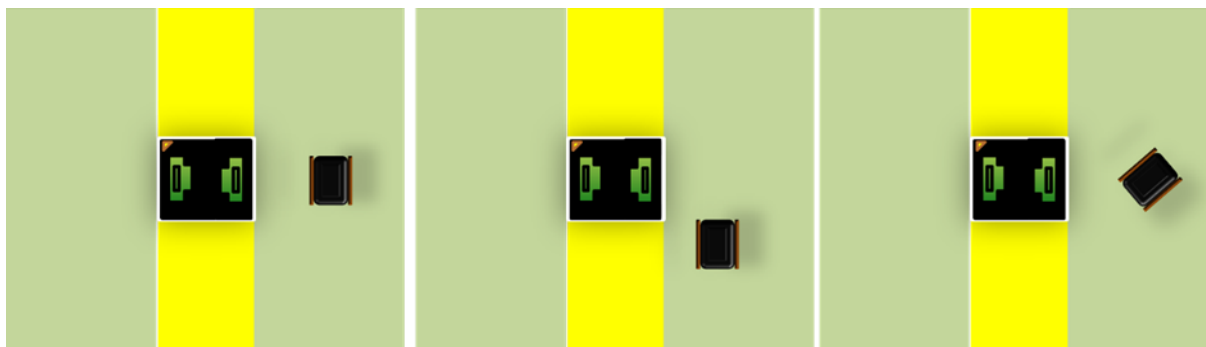


Figure 8 Guideline for placement of a component on the side of the sensor.

In case of having multiple components and objects nearby and if the radar performance is impacted by the objects in proximity, it is recommended to shield the sensor by creating a conductive tapered wall around the sensor. Figure 9 shows a model of such a shield can. The inner-walls of the can are tapered and conductive coated, in order to minimize the unwanted reflections.

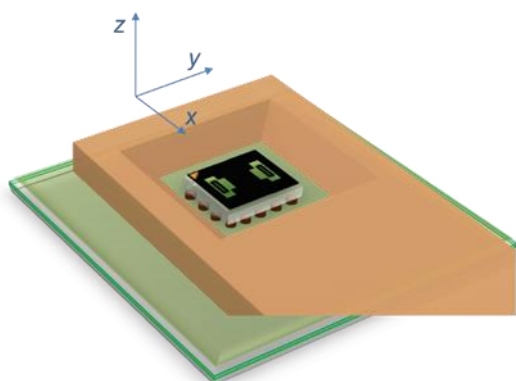


Figure 9 Tapered shield wall designed to prevent unwanted reflections from components placed close to the radar sensor.

3.4 A111 Decoupling capacitors

Ideally, the decoupling capacitors should be placed on the opposite side of the PCB from the sensor, but as close as possible to the via connecting the top and bottom layer. If manufacturing process allows, the via can be placed directly on the A111 VIO ball. If that is not possible, the impedance between the A111 VIO ball and the decoupling capacitor should be minimized. In practice, that means that the via should be placed as close as possible to the VIO balls on A111 and the trace between the A111 balls and the via, as well as the trace between the via and the decoupling capacitor, should be as short as possible. In Figure 10 an example of how to place the via and decoupling capacitor is shown. A four-layer PCB is shown in the example and the components and traces are highlighted in red.

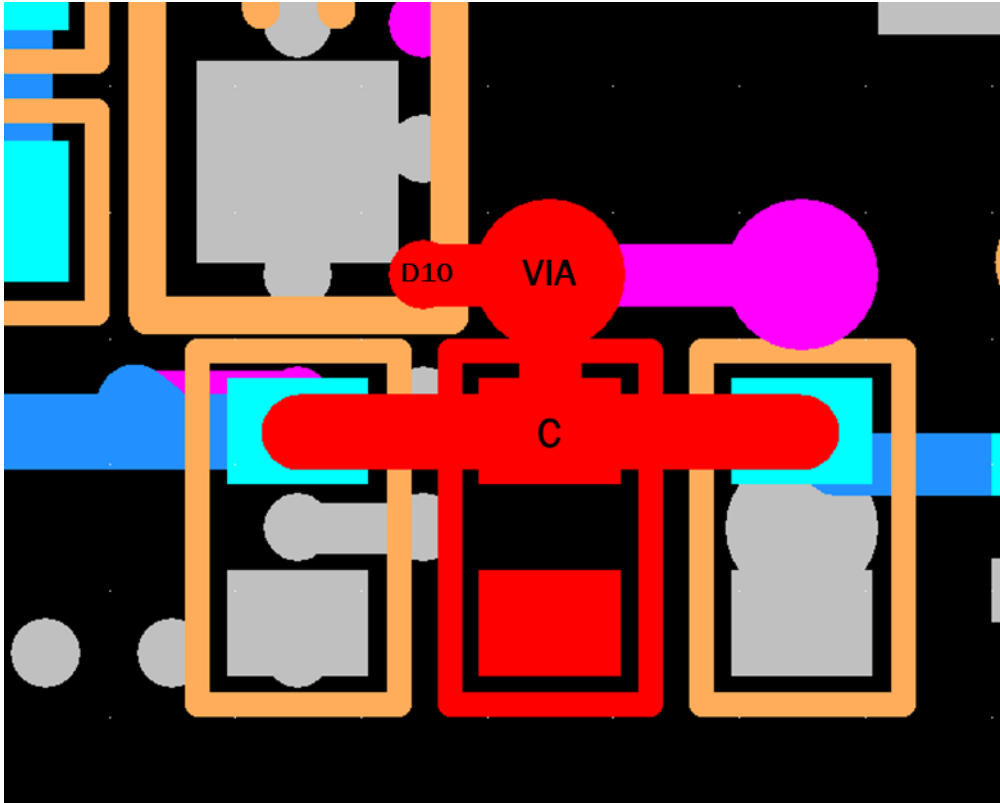


Figure 10 An example how to place the Layer 1:4 via and decoupling capacitor C (Layer 4) that decouples ball D10 on A111 (Layer 1). All components with orange component outlines are placed on Layer 4 while the A111 is placed on Layer 1.

3.5 A111 Crystal

Ideally, the crystal and its tuning capacitors should be placed on the opposite side of the PCB from the sensor, but as close as possible to the via connecting the top and bottom layer. If manufacturing process allows, the via can be placed directly on the A111 XIN/XOUT balls. If that is not possible, the impedance between the A111 XIN/XOUT balls and the crystal should be minimized. In practice, that means that the via should be placed as close as possible to the XIN/XOUT balls on A111 and the trace between the A111 balls and the via, as well as the trace between the via, the tuning capacitor and the crystal pads, should be as short as possible. In Figure 11 an example of how to place the crystal, tuning capacitors and vias is shown. A four-layer PCB is shown in the example and the components and traces are highlighted in red.

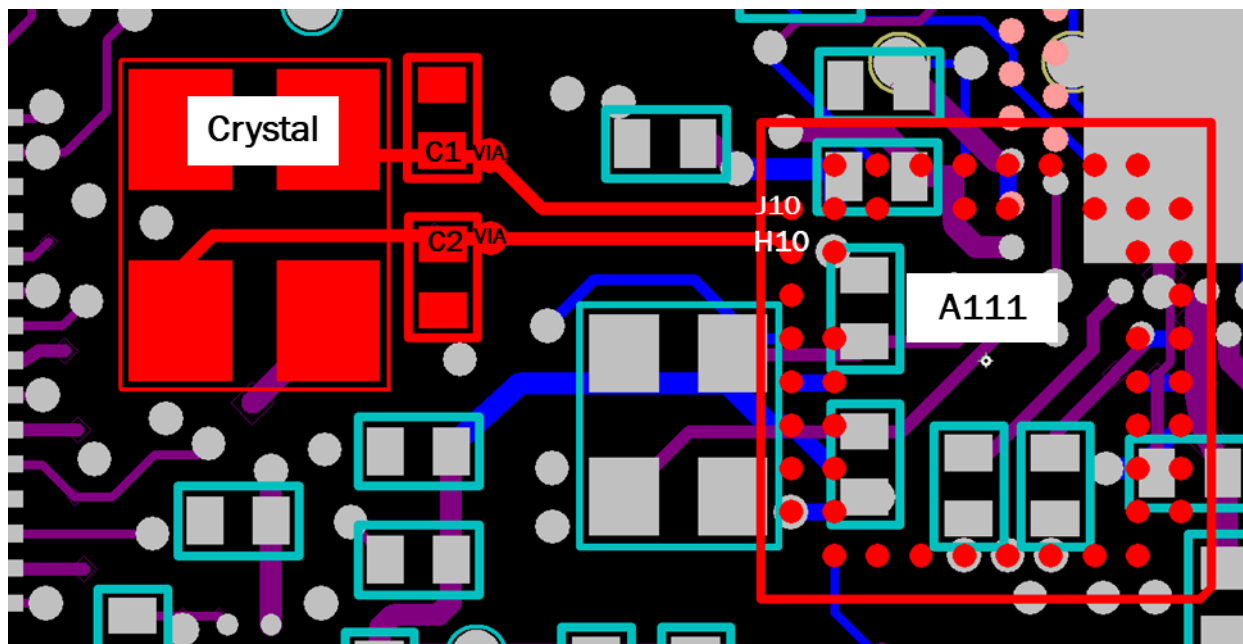


Figure 11 An example how to place the A111 crystal (Layer 4), its tuning capacitors (C1, C2, Layer 4) and vias (Layer 1:4). The crystal is connected to balls J10 and H10 on A111 (Layer 1). All components with light blue component outline are placed on Layer 4 while the A111 is placed on Layer 1.



4 Physical Integration

EM waves can interact with the objects and the media in which they travel. As EM waves propagate, they can be reflected, refracted, or diffracted. These interactions cause the radar pulse to change the direction and to reach the areas which would not be possible if the radar pulse travelled in a direct line.

This chapter provides the integration guidelines for simplified sensor cover scenarios. In any case, it is important to carefully design and characterize the integration to ensure that the desired performance is obtained. The radiation pattern presented in the A111 datasheet (www.developer.acconeer.com), shows the sensor performance when integrated in free space.

4.1 Radome integration

A radome is a structural enclosure that protects a radar assembly. Radomes are generally made of materials which are mainly characterized by their dielectric properties. Dielectric materials have a characteristic impedance of

$$Z_d = \frac{Z_0}{\sqrt{\epsilon_r}}$$

where ϵ_r is the dielectric constant relative to the free space and Z_0 is the wave impedance in free-space.

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377 \Omega$$

When an EM wave hits a dielectric material at a normal incident angle, the reflection coefficient is defined as

$$\Gamma = \frac{Z_d - Z_0}{Z_d + Z_0} = \frac{\sqrt{\epsilon_0} - \sqrt{\epsilon_r}}{\sqrt{\epsilon_0} + \sqrt{\epsilon_r}}$$

The transmission coefficient is defined as $T = 1 + \Gamma$. It is important to select dielectric materials for the radome such that the reflection coefficient has a low value. Therefore, a low dielectric constant material will minimize the reflections and reduce the impact on the radiation pattern and insertion loss. Typically, radomes are made of plastic and the dielectric constant of common plastic (ABS, PC, Teflon, PP) is less than 3, therefore, reflection coefficient for plastic materials is usually low. To further optimize the radome integration, shape of the radome, distance to the radar and the thickness of the radome needs to be considered in the design.

Figure 12 shows a scenario where a 1mm thick radome made of ABS plastic is placed at different distances, D , from the radar. The amplitude variation of the reflected waves from the radar target can be seen in the measured results shown in Figure 13. The variation of the amplitude is explained by the standing wave phenomena. The transmitted wave (indicated as blue in Figure 14) travels in the air medium until it reaches the second medium (plastic cover). Depending on the properties of the second medium, part of the energy will be transmitted through the medium and part of it will be reflected. The reflected pulse (indicated as yellow in Figure 14) will travel back to the PCB and be reflected again (indicated as red in Figure 14). Depending on the distance D , the transmitted wave and the reflected pulse can add up coherently or noncoherently. The maximum and minimum occur at multiples of the half wavelength of the radar pulse. The impact of the pulse length is visible in the measurement results (Figure 13). When the distance D gets larger than the pulse length, the standing wave disappears.

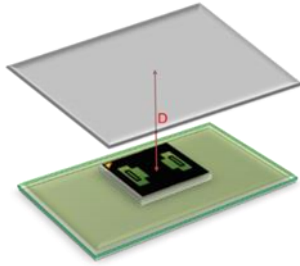


Figure 12 Placement of the radome in relation to the sensor.

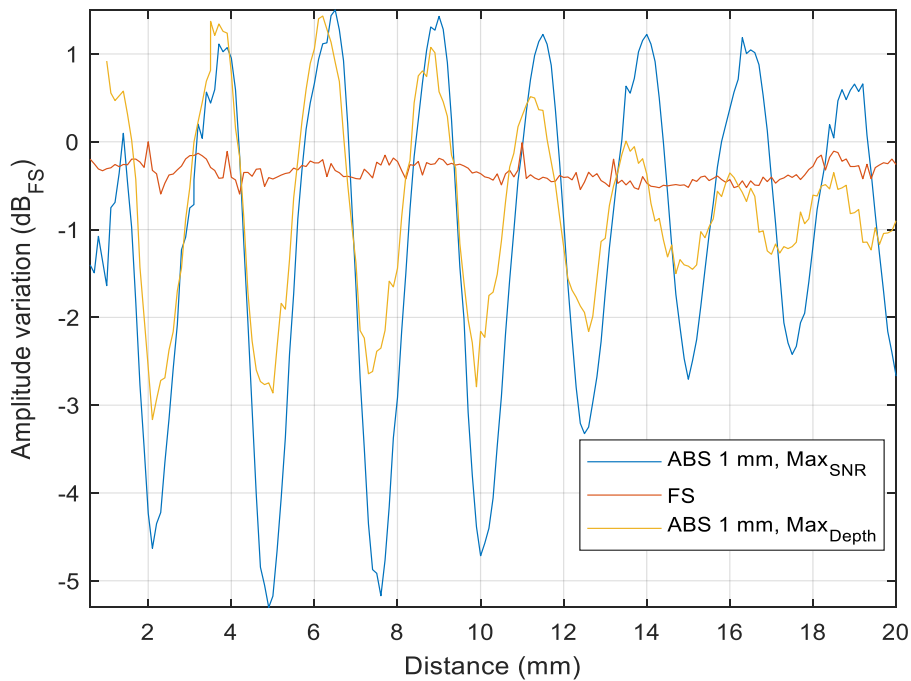


Figure 13 Measured reflected power from the target versus the radome to sensor distance for two different service profiles (ACC_SERVICE_ENVELOPE_PROFILE_MAXIMIZE_SNR and ACC_SERVICE_ENVELOPE_PROFILE_MAXIMIZE_DEPTH_RESOLUTION). Amplitude is normalized by the maximum value of Free Space.

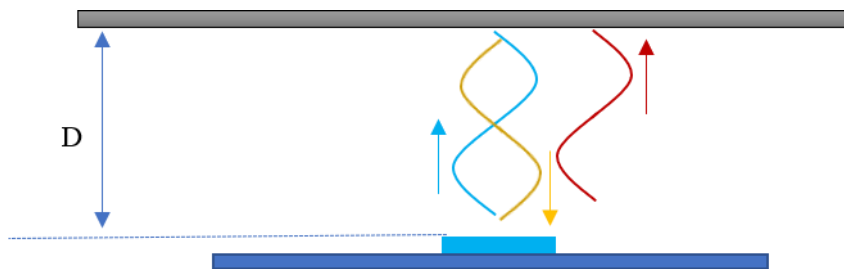


Figure 14 Illustration of the transmitted pulse and the reflected pulses (from plastic cover and the PCB).



4.2 Radome thickness

When an EM wave travels in a dielectric material, its effective propagation speed and the wavelength will change depending on the dielectric material:

$$c_{eff} = \frac{c_0}{\sqrt{\epsilon_r}}, \lambda_{eff} = \frac{\lambda_0}{\sqrt{\epsilon_r}}$$

where ϵ_r is the dielectric constant of the material, c_0 is the speed of light in free space, i.e. 3×10^8 and λ_0 is the free space wavelength ($\lambda_0 = 5mm$ for A111).

Reflections happens at the air-dielectric interfaces and the thickness of the dielectric medium determines the phase shift of the reflected wave from dielectric-air interface. Figure 15 shows a simplified model of the transmission and reflections of the waves between air-dielectric. Reflections from the second bounce and above are neglected in this model. When the wave impinges the air-dielectric interface, part of it reflects (r_{01}) and part of it transmits (t_{01}). The thickness of the dielectric material will cause the wave to shift phase by:

$$\theta = \frac{2\pi}{\lambda_{eff}} h$$

where h is the thickness of the dielectric. When the wave reaches the dielectric-air interface ($t_{01}e^{-j\theta}$), another transmission ($t_{10}t_{01}e^{-j\theta}$) and reflections ($r_{10}t_{01}e^{-j\theta}$) happens. Notice that the wave will have a sign change when the reflection happens, $r_{10} = -r_{01}$. At the lower dielectric-air interface, the amplitude of the wave is $-r_{01}t_{01}e^{-2j\theta}$, where the wave has traveled a distance of $2h$.

If we assume a half-wavelength-thick radome, the round trip of the wave inside the radome will introduce a 360-degree phase shift. Hence, the reflected wave into the air has a $-r_{01}t_{10}t_{01}$ amplitude. In this case, the reflected waves, $t_{10}t_{01} \approx -r_{01}$ and r_{01} will cancel out. Therefore, to minimize the reflections, the thickness of a single layer radome should be half-a-wavelength or a multiple of it.

$$h_{optimum} = n \frac{\lambda_{eff}}{2}, \quad n = 1, 2, 3, \dots$$

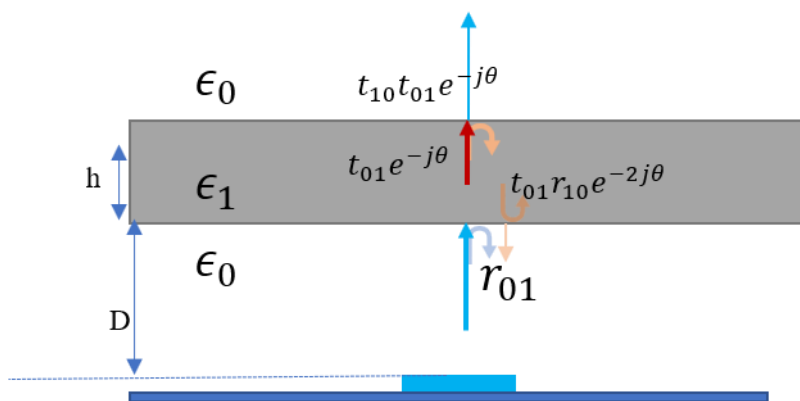


Figure 15 Incident wave impinging the radome at the normal incident angle. Transmission and reflection of the wave at the interfaces of two mediums.

As an example, a plastic sheet made of ABS with different thicknesses was selected for the test measurement. If we assume dielectric constant of ABS to be 2.6 (the dielectric constant can vary depending on the vendor), the thickness of the half-a-wavelength-thick radome is calculated to be



$$h = \frac{\lambda_{eff}}{2} = 1.55 \text{ mm}$$

Figure 16 shows the amplitude variation of the reflected wave from the radar target when the distance between the sensor and the radome is varied for different radome thicknesses. A thickness of 1.6 mm, which is very close to the thickness of half-a-wavelength, has the minimum impact on the amplitude variation. It is worth to mention that when the thickness is set to quarter-of-a-wavelength, the amplitude variation becomes maximum. When the radome thickness is set to quarter-of-a-wavelength, the round trip of the wave inside the radome leads to a 180° phaseshift.

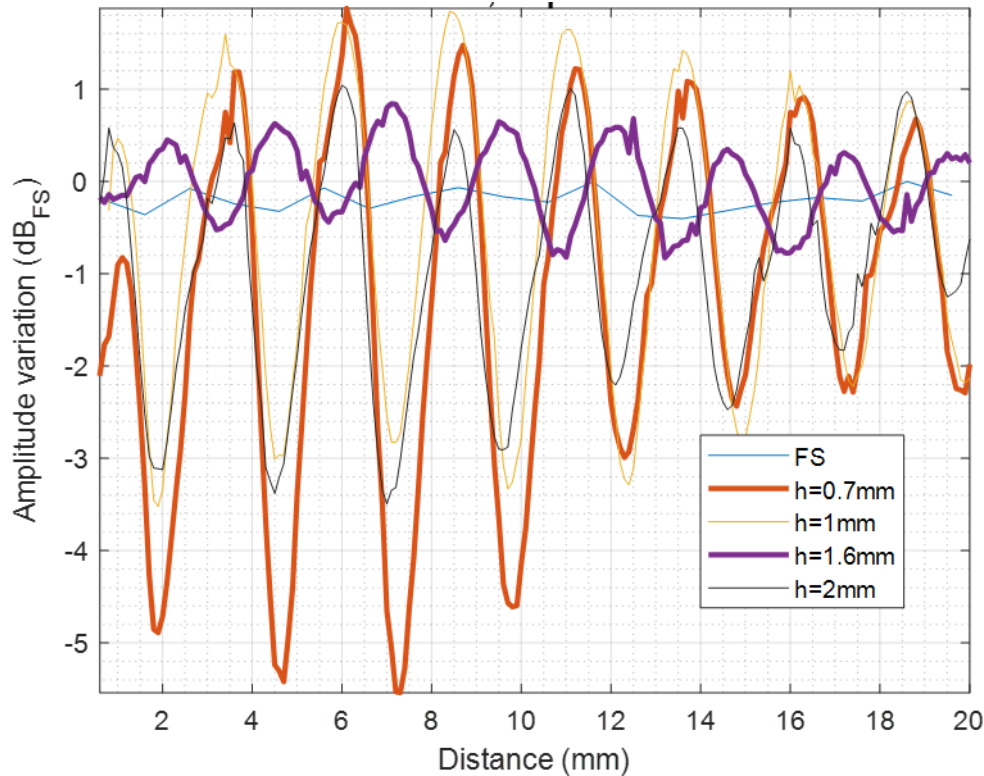


Figure 16 Impact of the thickness of the radome (made of ABS) on the reflected amplitude variation. The amplitude is normalized to maximum value of the Free Space (FS). Profile set to ACC_SERVICE_ENVELOPE_PROFILE_MAXIMIZE_SNR.

If absolute measurements are required for a certain use case, it is advised that an additional offset is added to the distance measurement. The reason for this offset is that the propagation delay caused by the radome must be compensated. This additional offset is obtained by making reference measurements, and it will also allow you to place the reference plane at the desired location for your product.

4.3 Radome distance

The reflected waves from the radome wall should be in-phase with the transmit waves, which leads to the optimum distance of

$$D_{optimum} = n \frac{\lambda_0}{2}, \quad n = 1, 2, 3, \dots$$



The optimum distance is valid if the thickness of the radome is optimum as well. Otherwise, to have a minimum insertion loss on the received signal, the distance to the sensor should follow the marginal criteria below:

$$n \frac{\lambda_0}{4} - \delta < D < n \frac{\lambda_0}{4} + \delta, \quad n = 1, 3, 5, \dots$$

In order to have zero insertion loss δ is determined to be 0.5 mm.



4.4 Impact on the radiation pattern

The radiation pattern of the integrated antennas will be affected by the dome that is put on top of the sensor. Figure 17 shows the measured radar loop pattern for three different materials, ABS plastic, gorilla glass and free space.

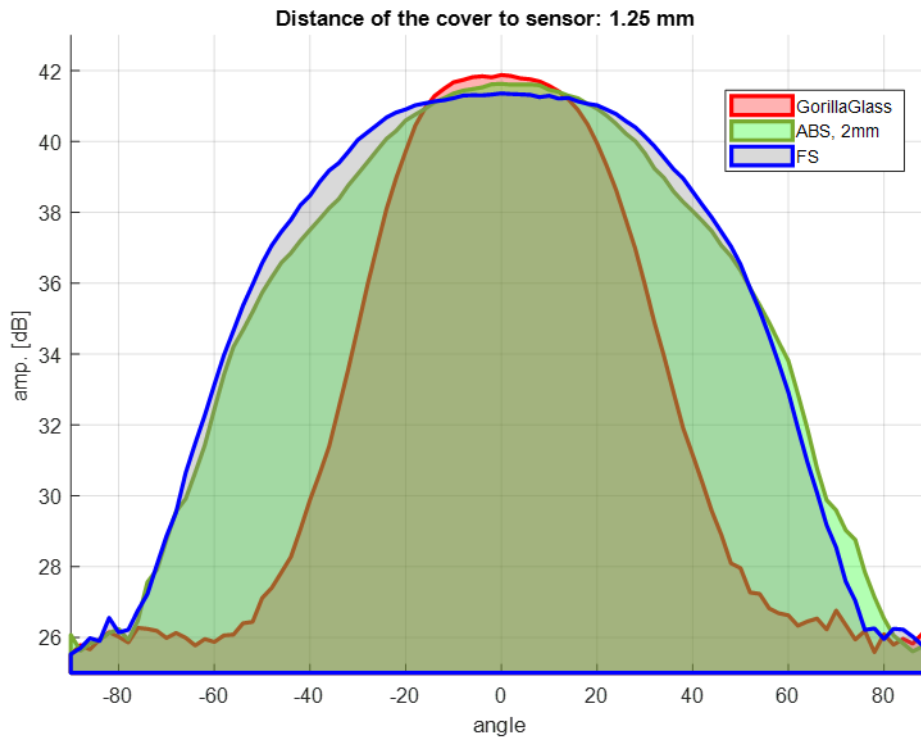


Figure 17 Impact of the different materials on the radiation pattern, H-plane.

Figure 18 shows the radar radiation pattern when a radome made of ABS with 2mm thickness is placed at distances corresponding to the harmonics of the quarter-of-a-wavelength of the radar pulse. The reference case is FS (Free Space i.e. no cover). Since the radome thickness is not optimal, distances which correspond to odd harmonics of the quarter-of-a-wavelength have the minimum impact on the radiation pattern.

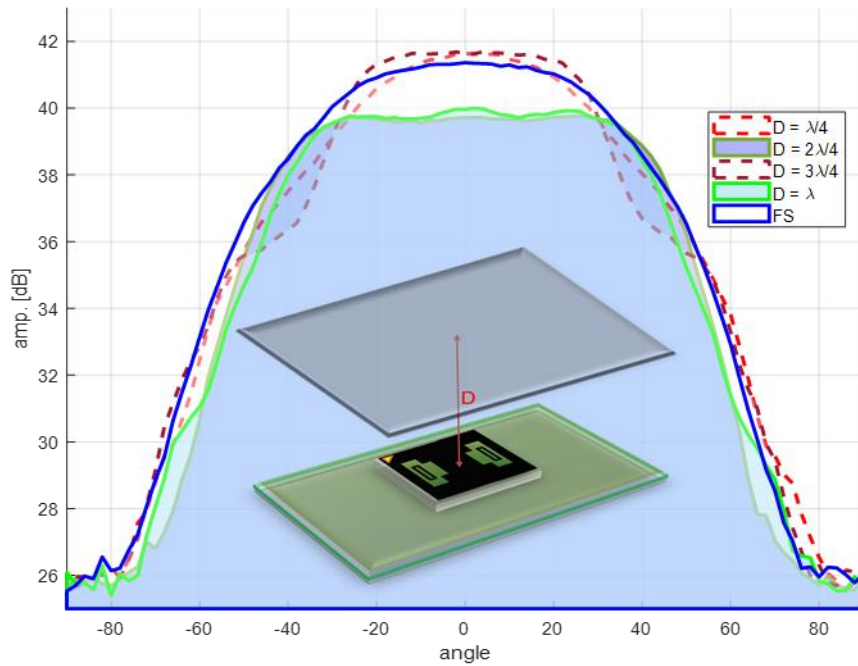


Figure 18 Impact of the radome-to-sensor distance on the radiation pattern (H-plane).

It is not recommended to place the cover directly on the sensor. Figure 19 shows the radiation pattern on the H-plane when the cover (ABS plastic sheet) is located on top of the sensor. In comparison with Free Space, there is around 3 dB loss on both max. power and total radiated power for this case.

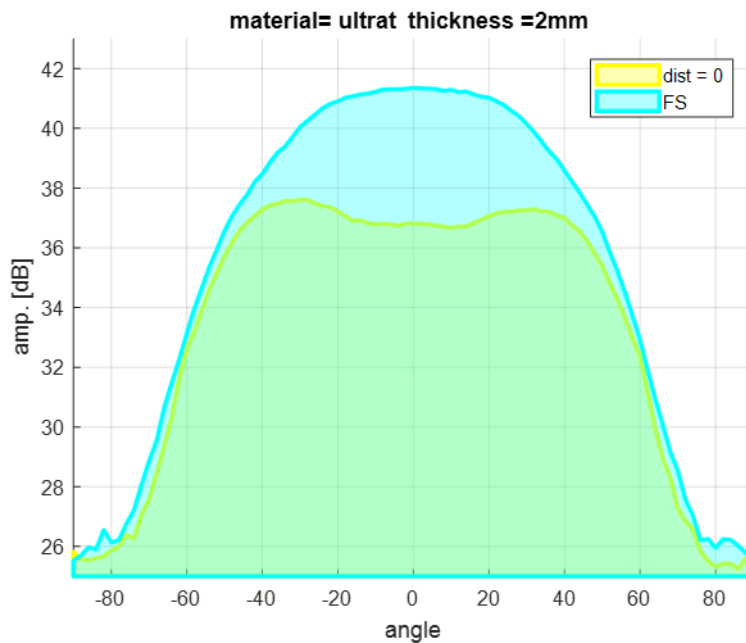


Figure 19 Radiation pattern on H-plane, cover placed directly on the sensor vs Free Space.



4.5 Multi-layer radome integration

Radomes can also be constructed from a multi-layer dielectric. Particularly, where the thickness of a single layer dielectric is fixed, thus additional layer can be added to the radome which can act as an anti-reflection layer. Figure 20 shows the stack-up of a radome made of two dielectric layers and illustrates the scattering of waves in this scenario. In this scenario, the reflections formed at the interfaces of the different mediums can be cancelled if the condition below is satisfied:

$$r_{01} + t_{10}t_{01}r_{12}e^{-2j\theta} + t_{10}t_{21}r_{20}t_{12}t_{01}e^{-2j(\theta+\varphi)} = 0$$

The layer indicated with ϵ_2 dielectric constant is the main layer and the layer with the ϵ_1 dielectric constant is the matching layer. Depending on the degree of the freedom, one can find the optimum thickness or the optimum dielectric constant for the anti-reflection layer.

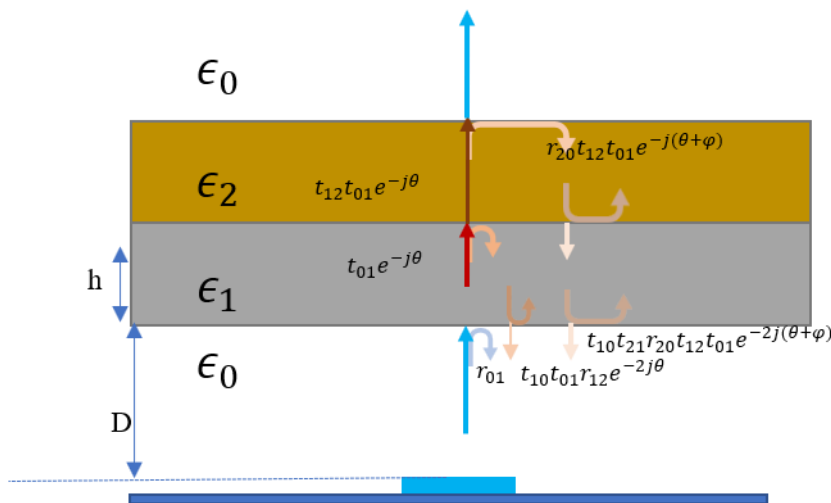


Figure 20 Illustration of the scattering waves for a two-layer radome.

Another approach is to use an EM simulation tool to find the characteristic of the anti-reflection layer. For example, Figure 21 shows a sensor integration scenario where the main layer of the radome is made of a special glass which has a high dielectric constant ($\sim 6-7$). Therefore, the wave impedance mismatch between the glass and the air becomes large. To reduce the mismatch, a matching layer with a lower dielectric is applied between sensor and the screen. To find the optimum dielectric value of the matching layer, the dielectric constant is varied in the simulation. It can be seen from the results shown in Figure 22 that the gain drops at least 2 dB in case 1, compared to case 2 where the matching layer has a dielectric constant of 3.

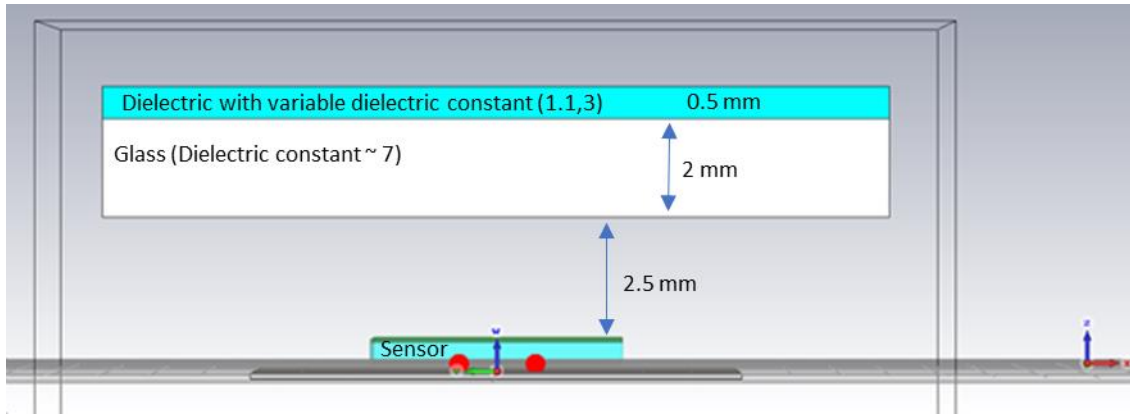


Figure 21 Simulation scenario: Sensor, air-gap, the matching layer and the screen.

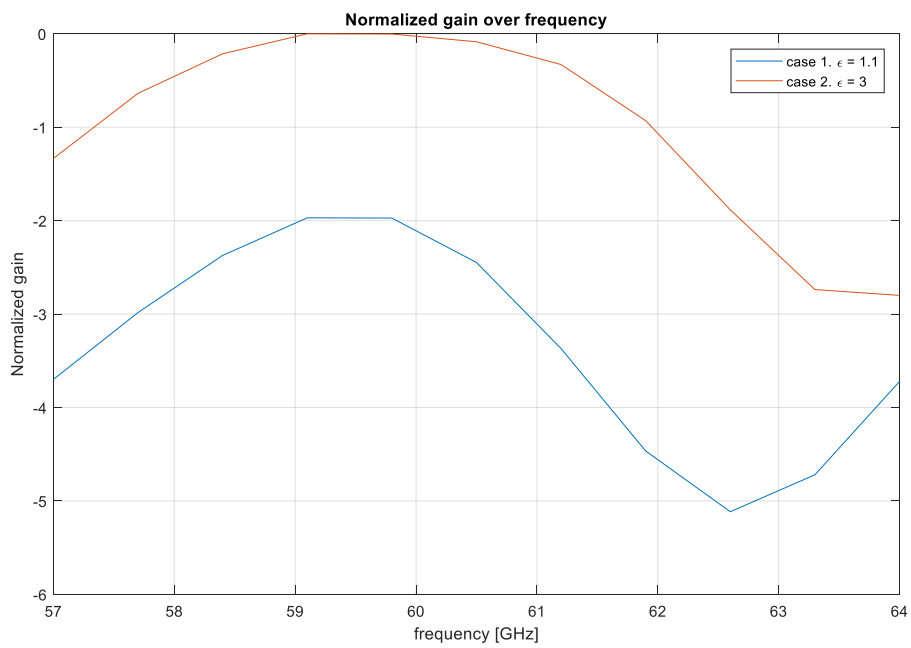


Figure 22 Normalized antenna gain where the matching layer dielectric constant is set to 1.1 and 3.



5 Physical Integration - Lens

The A111 sensor has a wide Half-Power Beam-Width (HPBW), typically 80° on the H-plane and 40° on the E-plane. For the applications where narrow beamwidth is required, additional lens antenna solution might be added to the sensor to achieve narrow beamwidth and high gain.

The major advantages of lens antennas are narrow beamwidth, high gain, low sidelobes. Their structures can be more compact and weigh less than horn antennas and parabolic reflector antennas.

Acconeer have designed two type of lens to narrow the beamwidth and improve the gain. First is the hyperbolic lens and the second is based on the phase correcting plate which is called Fresnel Zone Plate (FZP) lens. The shape of the hyperbolic lens is chosen so that the rays passing through the lens originating from the focal point will have the same phase shift, i.e. they will depart in-phase from the lens. In case of the FZP lens, the radius of each subzone and its thickness, are chosen so that rays passing through the edges of neighboring subzones originating from the focal point have the same phase shift.

Figure 23 depicts how the transition from the spherical waves to planar waves is done by two different types of lens. The main parameters for the lens design are the focal point, dielectric constant of the lens, and curvature (hyperbolic, zone radius and thickness).

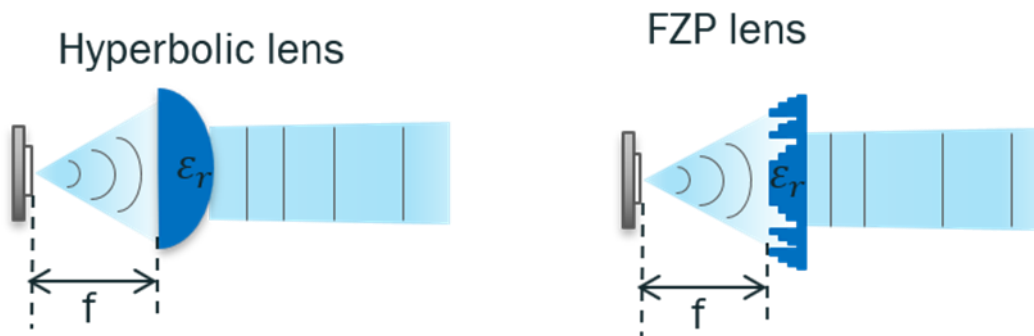


Figure 23 Hyperbolic and FZP lens located at the focal distance of the sensor.

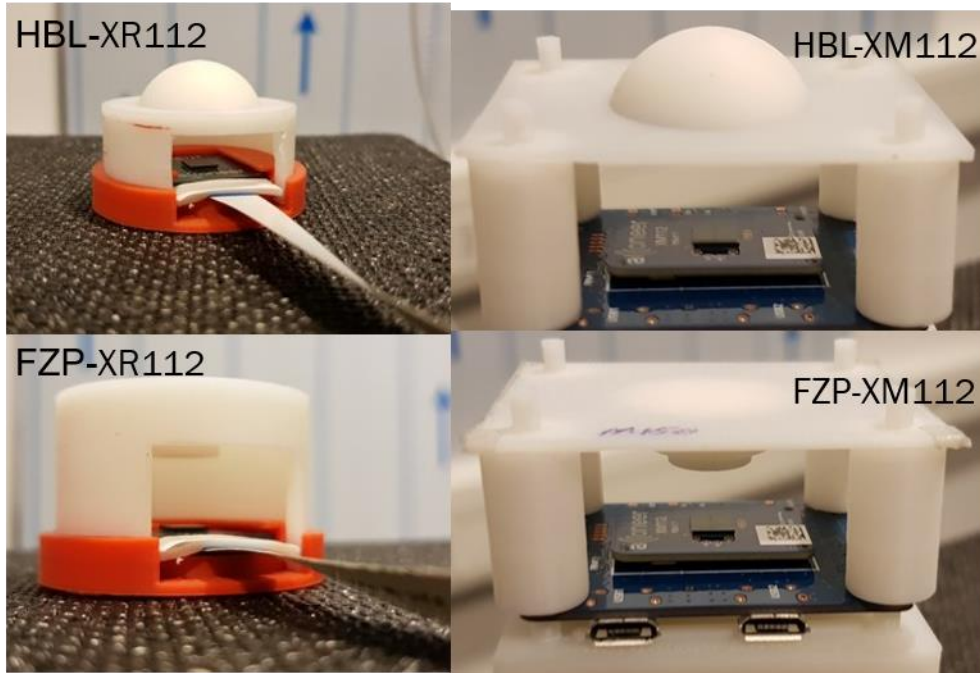


Figure 24 3D-printed examples of the hyperbolic and FZP lenses. The material used for printing is ABS plastic.

5.1 Focal distance

Radar loop measurement was done to characterize the focal point of the lens. The reflected power from a fixed radar target was captured for different sensor-to-lens distance. The distance between the sensor and target is to be in the far-field region, i.e. radar-to-target distance $> 1\text{m}$.

Figure 25 shows the radar loop gain of the integrated lens with the radome with respect to the free-space scenario for the XM112 module (see Figure 24 for the prototype pictures). The maximum gain happens at 7.5 mm distance for both lenses. Other maxima happen every half-of-a-wavelength ($\frac{\lambda_0}{2} = 2.5\text{ mm}$). The gain oscillation is due to the constructive and non-constructive interference of the transmitted and reflected waves between the lens surface and the sensor. The optimal placement can vary depending on the radome design. The measured results for the XR112 radome (Figure 26) indicate that the maximum gain happens at 8 mm distance. This can be due to the reflections from the radome side walls which can create interference. Therefore, it is important for every radome design to characterize the focal distance to find the optimum distance.

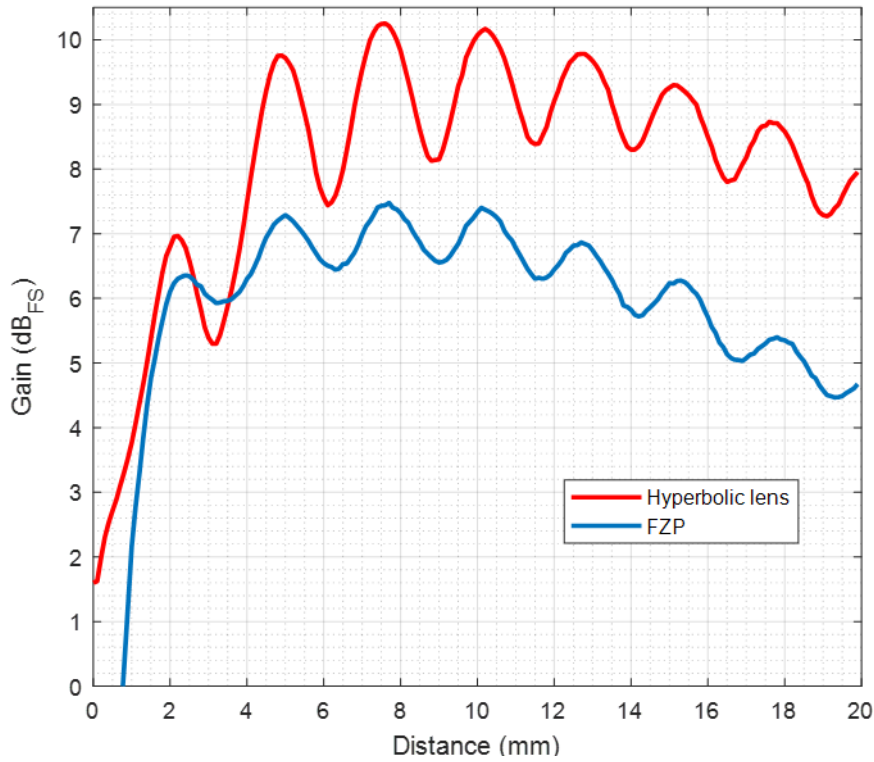


Figure 25 Gain variation of the lens versus the distance to the XM112 radome. The amplitude is normalized to Free Space (FS).

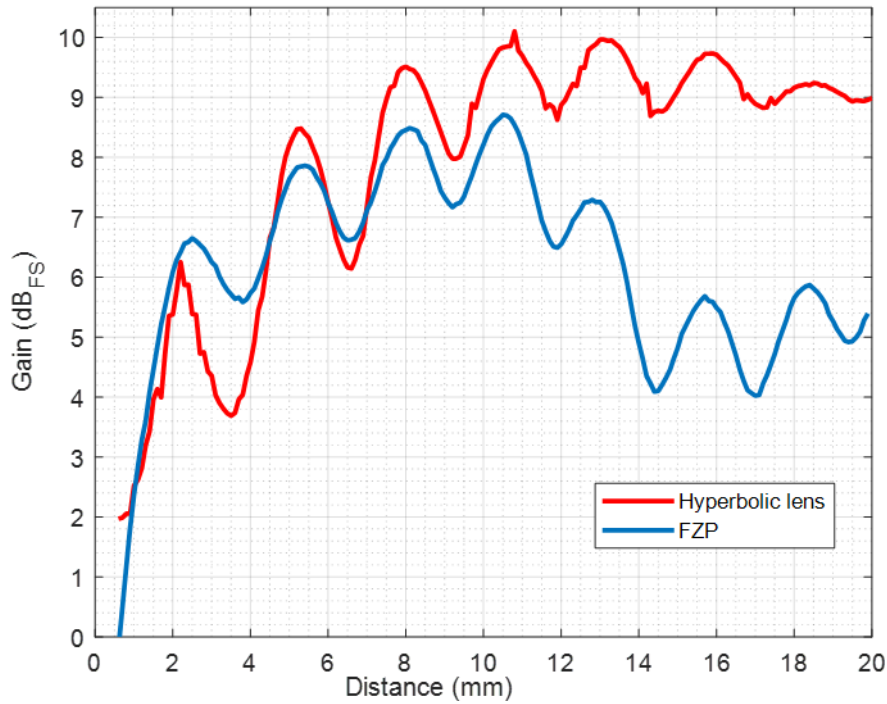


Figure 26 Gain variation of the HPL and FZP lens versus the distance to the XR112 radome. The amplitude is normalized to Free Space (FS).



5.2 Radiation pattern

Two focal distances, $D_{\text{sensor-lens}} = 2$ and 8 mm, are chosen for characterizing the radar loop radiation pattern of the lenses. Figure 27 and Figure 28 show the measured radar loop pattern for free-space, HPL and FZP lenses for the selected focal distances. The measured gain is slightly lower than the expected values (refer to Figure 25). This is due to tolerances of the distance which impacts the gain. If one considers the FZP lens, the distance tolerance of ± 0.5 and ± 1 mm results in 0.5- and 1-dB gain loss respectively.

Calculated HPBW for both focal distances are shown in Figure 29. When the focal distance is set to 2 mm, the radiated beam is less directive compared to when the focal distance is set to 8 mm.

To conclude, when a new radome is designed, it is very important to characterize the integrated lens and radome to optimize the design for the targeted application.

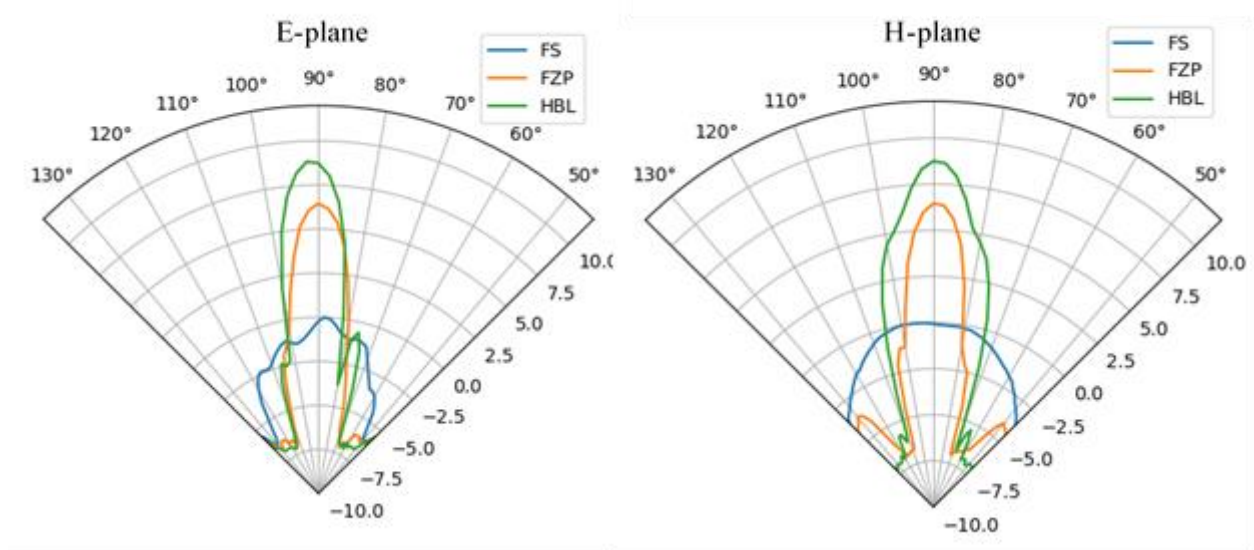


Figure 27 Radar loop radiation pattern of the sensor in Free Space and with lens. Distance from the lens to the sensor is set to 8mm. Radius is in dB scale normalized to Free Space maximum gain.

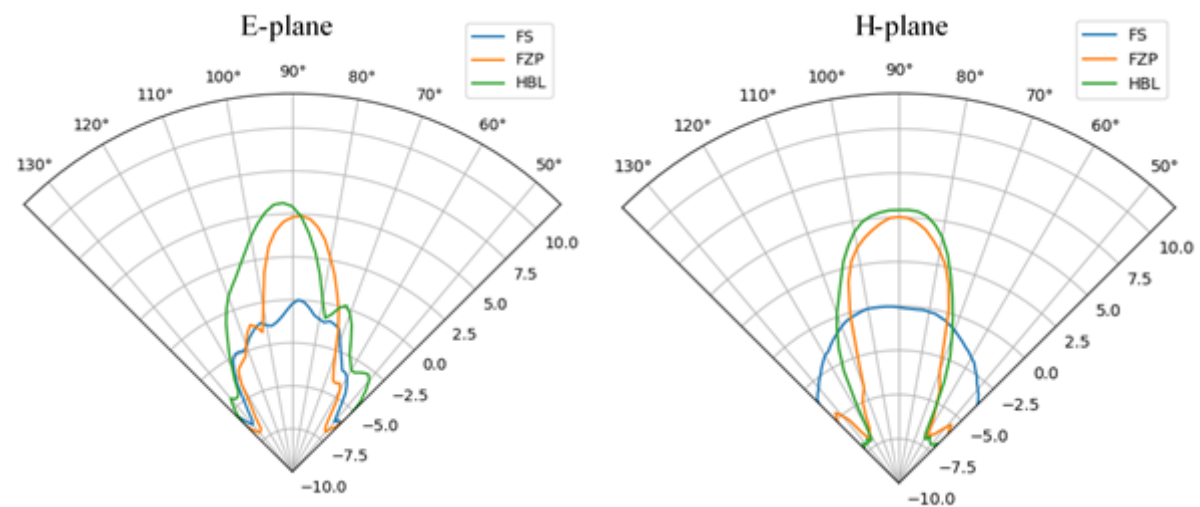


Figure 28 Radar loop radiation pattern of the sensor in Free Space and with lens. Distance from the lens to the sensor is set to 2mm. Radius is in dB scale normalized to free space maximum gain.

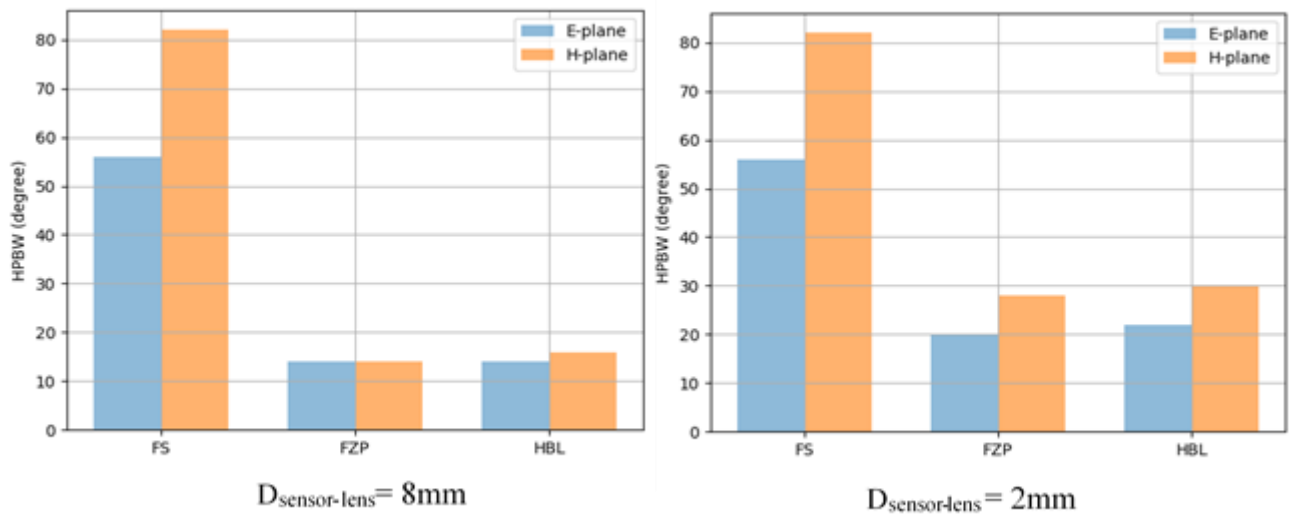


Figure 29 Half-power beam width for the FZP and hyperbolic lenses placed at a distance from the sensor of 8mm and 2mm respectively.

In Figure 30 the maximum gain of the lenses in the E-plane is shown for the two different focal distances.

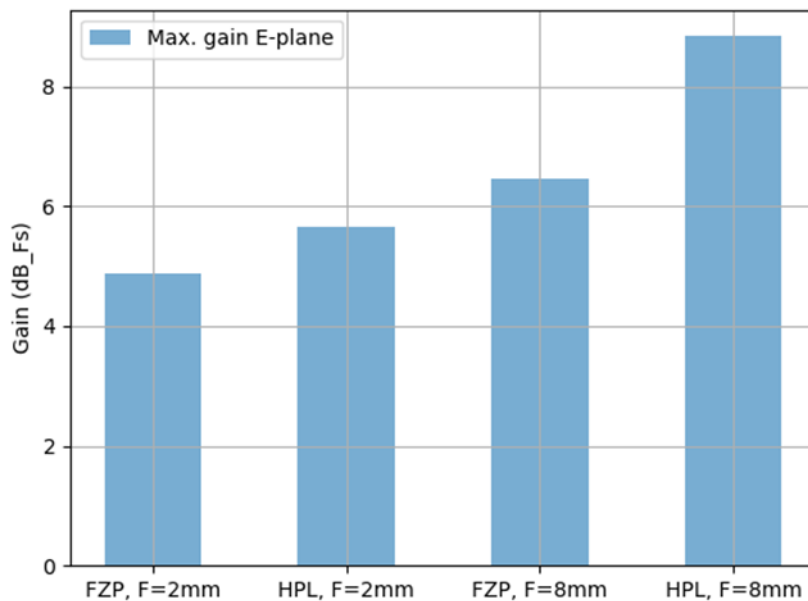


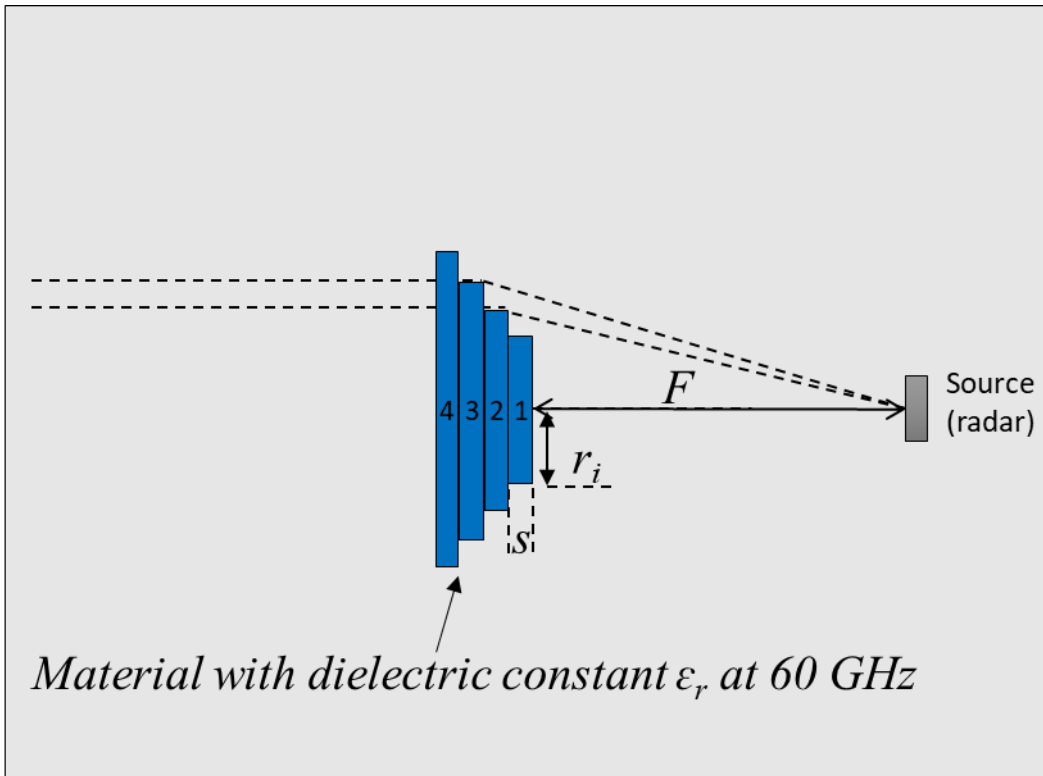
Figure 30 Gain of the FZP and hyperbolic lenses at E-plane for focal distances of 2mm and 8mm.

5.3 FZP Lens Design

The FZP lens characterized in the previous chapters was made of ABS plastic with a focal point distance of 2mm and 8mm. If other materials are to be used or if another focal point distance is needed, the dimensions of the FZP lens should be altered. In Figure 31, a detailed description of an



FZP lens is shown, as well as the equations needed to design one. For further details regarding FZP and hyperbolic lens design, refer to [5].



$$r_i = \sqrt{2F_i \frac{\lambda}{p} + i \left(\frac{\lambda}{p}\right)^2}, \quad i = 1, 2, \dots$$

$$s = \frac{\lambda}{p(\sqrt{\epsilon_r} - 1)}$$

F : Focal point, input parameter

p : number of steps

λ : Wavelength in free-space: 5mm for 60GHz

ϵ_r : Dielectric constant of the material at 60 GHz

s : Thickness of each step

r_i : Radius for step i

Figure 31 Detailed description of an FZP lens and the equations needed to calculate its dimensions.

By using the equations in Figure 31, one concludes that a four-step FZP lens in ABS-M30 plastic ($\epsilon_r = 2.48$), with the focal point at 10mm, needs the following dimensions:



$$r_1 = 5.1\text{mm}$$

$$r_2 = 7.46\text{mm}$$

$$r_3 = 9.39\text{mm}$$

$$r_4 = 11.12\text{mm}$$

$$s = 2.17 \text{ mm}$$

$$\text{Total thickness of the lens: } 4 * 2.17 = 8.7 \text{ mm}$$



6 Appendix A: Materials

Table 1 Measured dielectric constant and loss tangent of different materials at 60 GHz [6].

Material	Dielectric constant	Loss tangent
ABS-M30 (three-dimensional printed)	2.48	0.008
Acrylic glass	2.5	0.0118
Alumina	9.3	0.0013
Fused quartz	3.8	0.0015
MACOR	5.5	0.0118
PLA (three-dimensional printed)	2.85	0.014
Polyethylene	2.3	0.0003
Polypropylene	2.2	0.0005
Polystyrene (Rexolite)	2.5	0.0004
Teflon	2.2	0.0002



7 References

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- [3] <https://developer.acconeer.com/download/xm112-datasheet-pdf/>
- [4] https://developer.acconeer.com/download/xc112_xr112-user-guide-pdf/
- [5] Thornton, John, and Kao-Cheng Huang. “*Modern lens antennas for communications engineering.*” Vol. 39. John Wiley & Sons, 2013.
- [6] Boriskin, Artem, and Ronan Sauleau, eds. “*Aperture Antennas for Millimeter and Sub-Millimeter Wave Applications*”. Springer, 2017.



8 Revision

Date	Version	Changes
2019-11-13	1.0	Original version



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