White Paper
June 2020

Radar wave propagation through materials

Walls and radomes

Abstract

This white paper focuses on electromagnetic (EM) wave propagation through materials. For radar systems, this is of interest when radar must pass through walls, or when designing radomes (cover casings for the radar system). In the process of designing a radome, you should always perform full EM simulation. However, the content of this white paper will help you to first estimate whether a radome can even be functional, and if so, how to choose the right materials for the radome.

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1 Introduction

The use case discussed in this document is as follows. A radar antenna emits a radar wave into air. The radar wave must travel through a material between the radar sensor and the desired target, as illustrated in ***Figure 1***. This document will not look at partial coverage of the path between radar and target. Neither will it discuss scenarios with multiple targets. It focuses only on materials that fully cover the path between the radar sensor and a single target.

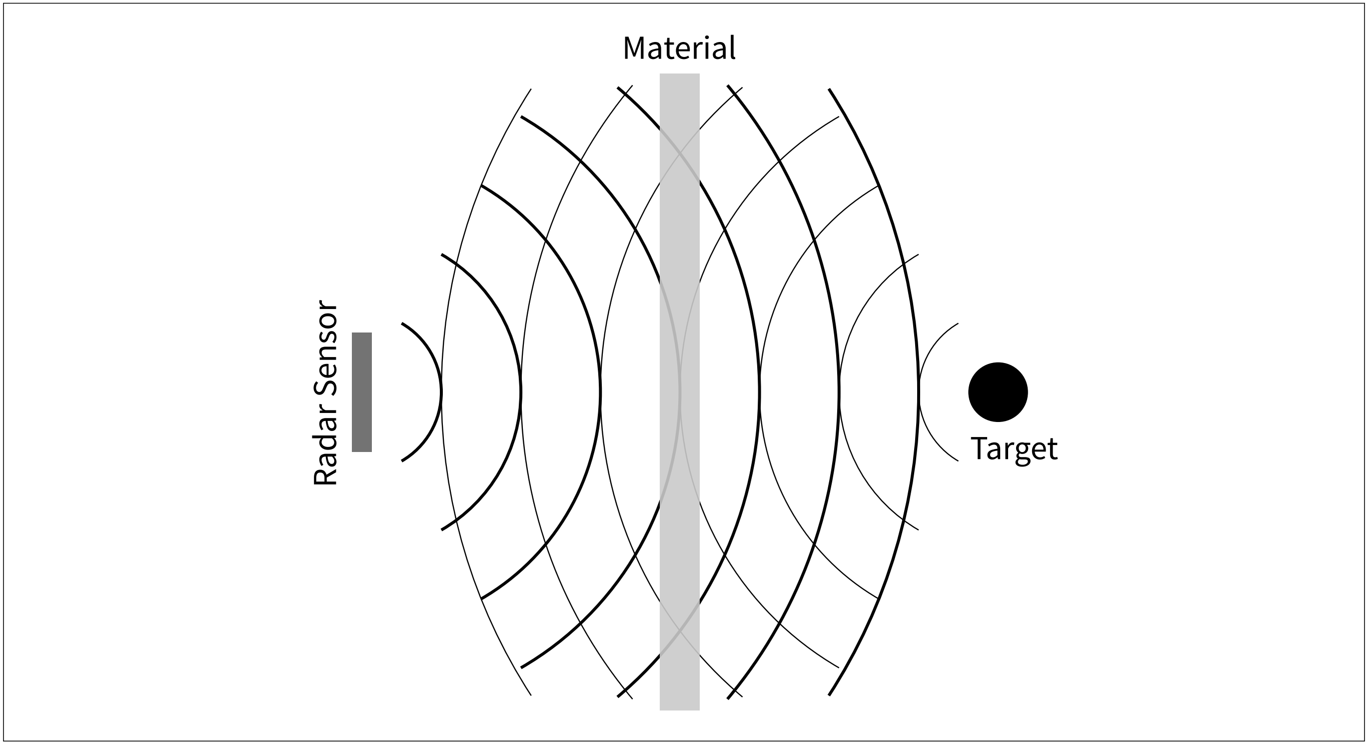

Figure 1 **Scenario with a material between the radar sensor and the desired target.**

2 Radome design cookbook

The cover of a radar sensor is called a "radome". Most people will read this document to help them understand how to design a radome and it is recommended to read the full document. The first section is a kind of "cookbook" on how to explain the design of a radome in simple terms.

The physics behind EM wave propagation can be difficult to grasp. This section therefore provides an overview, with more details in the chapters that follow. Most radome designs are simple, and you can design one in such a way that losses due to the radome are small and will hardly impact the radar system's performance. In the rare case of a complicated radome design, EM simulations will always be required to optimize its performance. In such cases, this cookbook can help you select the right materials as a starting point in the design process.

A radome will always slightly reduce the signal strength of the detected radar targets. Before starting the design process, it is therefore helpful to know the signal-to-noise ratio (SNR) budget. That means that in tests without a radome, you must determine how much lower the signal strength can be and have the radar algorithm still working. The losses due to the radome must fit within this SNR budget.

Here are some general guidelines for the choice of materials:

- Avoid metals because even thin layers show high attenuation for EM wave propagation (***Table 3***)
- Avoid poor dielectrics with high loss tangents
    - ***Table 2***
    - Contamination of the radome surface might absorb EM waves. For example, a 1 mm water film will cause more than 16 dB attenuation for 60 GHz radar.
- Avoid materials with high permittivity (***Table 1***)

When sticking to these guidelines, it should be possible to design a radome that causes less than 2 to 3 dB loss. In normal radar operation, an attenuation of 12 dB will halve the maximum detection distance. Therefore, 2 dB will reduce the maximum detection distance by about 11 percent.

Spacing between the radar antennas and the radome:

- Radomes in the near-field (***Equation 9***) will always impact the performance, and a detailed study will require EM simulations.
- Ideally, place the radome at a distance of $\lambda/2$ from the antennas to minimize the effect of back reflections on the overall radar system.
    - Distances of $\lambda/4$ or an odd multiple of that will have the biggest impact on the radar system.
    - Typically, this effect is weaker than the losses due to reflections. For example, if the losses due to reflections are in the order of 2 dB, the effect due to the distance is most of the time below 0.5 dB. (However, the exact impact will depend on the antenna and the Power Amplifier (PA) driving the antenna.)
- If the distance between radar antennas and the radome must be minimized at all costs, try to avoid distances smaller than $\lambda/10$. There, EM simulations are highly recommended.

Shaping the Field of View (FoV):

- Try to simplify the requirements. For example, can a simple tilting of the sensor shape the FoV so that no lenses are required?
- Increasing the FoV angle will always require lenses or stacks of dielectric materials. It is recommended to always simulate the behavior of lenses.
- Decreasing the FoV:
    - Sharp edges in the FoV can be achieved with sheets of metal. However, as metal is a strong reflector (close to the radar antennas), EM simulations will have to be performed.
    - Radar beam collimation will always require lenses or stacks of dielectric materials. It is recommended to always simulate the behavior of lenses.

- If you require a wide FoV in a single direction, orient the sensor so the polarization of the radar system is perpendicular to the wide FoV. (In this way, the wide angle will correspond to p-polarization at the radome which shows smaller reflections than s-polarization.)
- For a worst-case estimate of the angle dependent losses, use the ones from s-polarization (in the polarization direction of the radar sensor).

Vibrations:

- Mount the whole radar system rigidly so there are no vibrations.
- Avoid vibrations between the radome and the radar antennas at all costs!

3 Fundamentals

For electromagnetic (EM) wave propagation, you must distinguish between reflections on surfaces (***Chapter 3.1***) and absorption in dielectric materials (***Chapter 3.2***). In conductors, you need to consider the skin effect (***Chapter 3.3***).

3.1 Reflections on dielectric surfaces

Reflections on these surfaces happen when radar waves have to pass through dielectrics such as window glass. Snell's law and the Fresnel equations describe the behavior of EM waves when they encounter these surfaces.

Snell's law describes the relationship between the angle of the incident beam and the angle of the transmitted beam, as shown in ***Figure 2***. The incident beam has an angle of θ_i to the normal angle of the surface between two materials. The resulting transmitted beam will have an angle of θ_t to the normal angle.

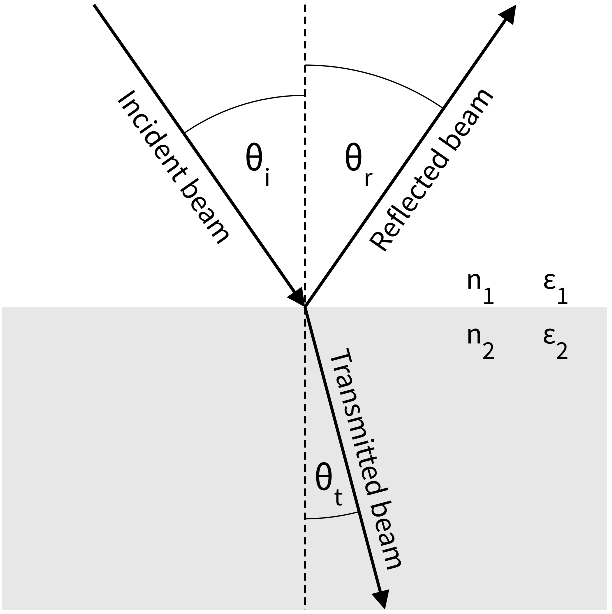

Figure 2 **Illustration of Snell's law.**

The material on the incident beam side has a relative permittivity $\varepsilon_r = \varepsilon_1$, and the material on the transmitted side has a relative permittivity $\varepsilon_r = \varepsilon_2$. As most dielectrics are non-magnetic, the refractive index of a material is defined as the square-root of the relative permittivity:

$$n = \sqrt{\varepsilon_r}.$$

Equation 1 **Refractive index**

The wavelength in the material is defined as $\lambda_{\text{material}} = \frac{\lambda_{\text{vacuum}}}{n}$ .Snell's law states that the product of the refractive index and the sine of the angle are constant at a surface. Therefore, you can write:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

Equation 2 **Snell's law**

where n_i and θ_i are the refractive index and the ray's angle in the material with relative permittivity ε_i. With this law, you can compute the direction of the angle of the transmitted beam with a known angle of incidence and known refractive indices (permittivities) at the surface. It allows computation of lenses to alter radar beam divergences - see ***Chapter 5.1*** for details. The important thing to remember about Snell's law is that the direction of travel in a material changes. For an example of this behavior in optics, imagine an object at the bottom of a water filled swimming pool. If you try to reach the object with a long straight stick, you will have to aim at a different position than where the object appears to be. The reason for this is diffraction at the surface of the water.

The shape of the surface of the dielectric material is also crucial. The equations in this chapter assume a flat surface. If you have a curved or rough surface, you have to consider a small section of the surface and approximate it as being flat. Typically, a roughness of below one thirtieth of the wavelength can be ignored, and the surface treated as flat.

In order to calculate how much of the incident beam is reflected and how much is transmitted, you will need to use Fresnel equations. In this way, you can distinguish between p- and s-polarization: p-polarization is the polarization parallel to the surface. In the case of ***Figure 2***, the p-polarization would protrude from the figure in a third direction. The s-polarization would be perpendicular to the beam's directions of travel in the plane shown in ***Figure 2***. For a detailed description of p- and s-polarization, refer to ***Chapter 5.2***. All polarizations are superpositions of p- and s-polarization. First, you need to assume that the angle of incidence is equal to the angle of reflection $\theta_i = \theta_r$.

$$R_p = \left|\frac{n_1\cos(\theta_t) - n_2\cos(\theta_i)}{n_1\cos(\theta_t) + n_2\cos(\theta_i)}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2} - n_2\cos(\theta_i)}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2} + n_2\cos(\theta_i)}\right|^2$$

$$R_s = \left|\frac{n_1\cos(\theta_i) - n_2\cos(\theta_t)}{n_1\cos(\theta_i) + n_2\cos(\theta_t)}\right|^2 = \left|\frac{n_1\cos(\theta_i) - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2}}{n_1\cos(\theta_i) + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2}}\right|^2$$

Equation 3 Fresnel equations

The second set of formulas use Snell's law on the first part of the formula. The transmittance is defined as one minus reflectance, $T = 1 - R$. The transmittances and reflectances for p- and s-polarization are illustrated in ***Figure 3***. For p-polarization, there is an angle with zero reflection, called the Brewster angle. For the transition from a material with higher refractive index to a material with lower refractive index, internal total reflection will not allow any EM wave to escape the material with higher refractive index beyond a certain angle. But the most important message to take away from these formulas is that the two polarizations are transmitted differently. Typically, the polarization of the emitted radar waves is not-aligned with the surface of the material. Therefore, the emitted radar wave must be considered as a superposition of the two polarizations. As the two polarizations are transmitted differently, the total polarization of the radar wave will change when passing through a dielectric. For more details, see ***Chapter 5.2***.

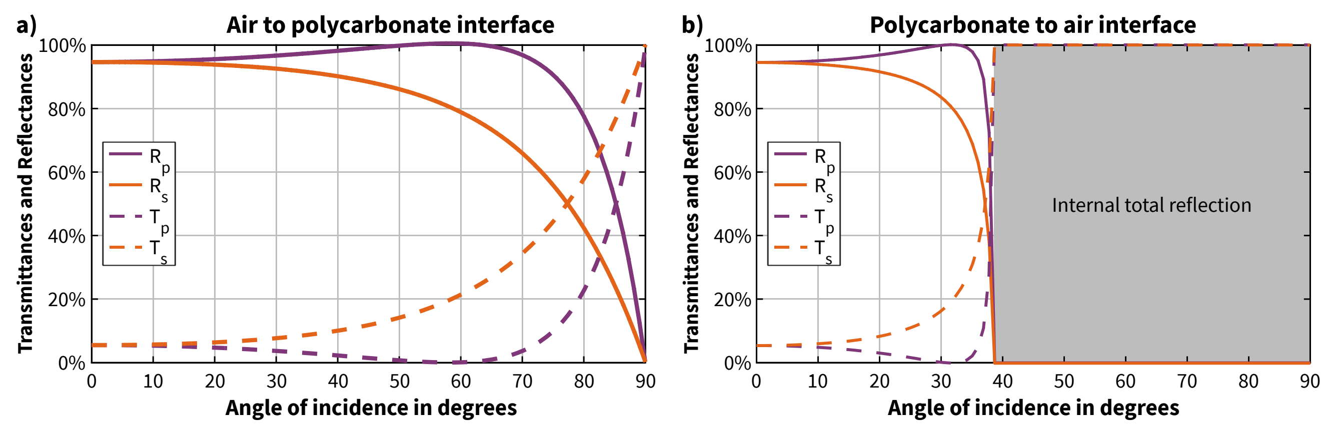

Figure 3 Transmittances and reflectances of transitions from air to glass (a) and glass to air (b)

For an angle of 0 degrees (normal angle to surface), the formulas for both polarizations simplify to

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2$$

Equation 4 **Reflection for an angle of incidence of 0 degrees**

Table 1 **Transmission through various materials for an angle of incidence of 0 degrees without absorption losses**

Material	**Relative permittivity ε_r**	$\frac{\lambda_{\text{material}}}{\lambda_{\text{vacuum}}}$ **in %**	**Single surface transmission**		**Air – material – air single pass transmission**		**Air – material – air double pass transmission**	
			in %	**in dB**	**in %**	**in dB**	**in %**	**in dB**
Poron	1.6[1]	79.1	98.6	-0.12	97.3	-0.24	94.6	-0.48
Teflon (PTFE)	2[1]	70.7	97.1	-0.26	94.2	-0.52	88.73	-1.04
Plexi glas	2.2[2]	67.4	96.2	-0.34	92.6	-0.67	85.7	-1.34
Polycarbonate	2.6[1]	62	94.5	-0.49	89.3	-0.98	79.8	-1.96
ABS	2.9[1]	58.7	93.2	-0.61	86.9	-1.22	75.6	-2.43
Polyamide-nylon	3[1]	57.7	92.8	-0.65	86.2	-1.29	74.2	-2.59
HPFS glass	3.8[1]	51.3	89.6	-0.95	80.4	-1.9	64.6	-3.8
Gorilla glass	≈ 7[1]	≈ 37.8	≈ 79.6	≈ -1.98	≈ 63.4	≈ -3.96	≈ 40.2	≈ -7.92
Zirconia	More than 20[3]	Less than 22.4	Less than 59.7	Less than -4.47	Less than 35.7	Less than -8.95	Less than 12.7	Less than -17.9

Note: ***Equation 4**, illustrated in **Table 1**, shows a general behavior. The reflections will be stronger if the change of refractive index is bigger. For example, if you want to place a radar motion sensor behind a cover, choose a material that has a refractive index (permittivity) as low as the air around it (which has a refractive index of about 1). This minimizes the term in the numerator, and also minimizes the (unwanted) reflections of the cover.*

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[1] Measured at Infineon lab.

[2] ***https://www.rfcafe.com/references/electrical/dielectric-constants-strengths.htm***

[3] Y. Oh, V. Bharambe, B. Mummareddy, J. Martin, J. McKnight, M. A. Abraham, J. M. Walker, K. Rogers, B. Conner, P. Cortes, E. MacDonald, J. J. Adams, "Microwave dielectric properties of zirconia fabricated using NanoParticle Jetting™", Additive Manufacturing, Vol. 27 (2019) p. 586-594

3.2 Absorption in a dielectric with loss

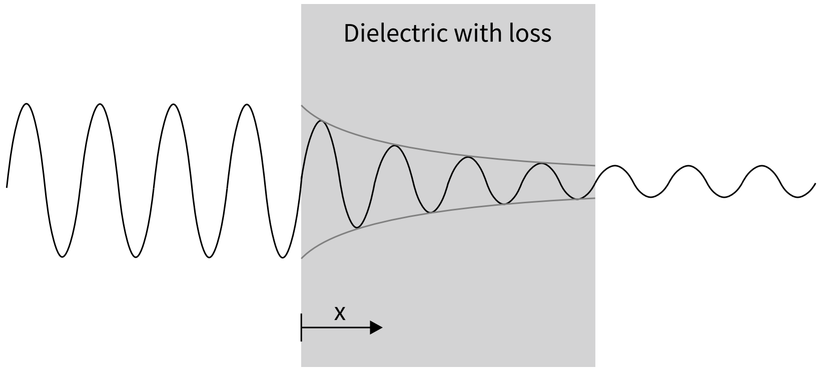

Figure 4 **Illustration of absorption in a material**

In the previous chapter, it was assumed that the dielectric material between the radar and the target was without loss. However, this is not always the case. Dielectrics with loss can significantly reduce the RF fields passing through them.

Figure 4 shows how radiation is attenuated in a dielectric with loss. The power of the radiation decreases exponentially over length. To describe dielectric loss, a complex permittivity can be used in Maxwell's equations:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

Equation 5 **Complex permittivity**

Another way to describe dielectric loss, is by using the loss tangent, which is defined as the angle in the complex plane of the complex permittivity:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

Equation 6 **Loss tangent**

If the material is also conducting, you can use $\tan\delta = \frac{\omega\,\varepsilon'' + \sigma}{\omega\,\varepsilon'}$, where σ is the material's conductivity and ω is the angular frequency. The loss tangent of a material is a material property, like its permittivity. To calculate the losses along the direction x, you can use:

$$P(x) = P(x = 0)\ \ e^{-\delta k x}$$

Equation 7 **Losses with loss tangent**

where $\delta = \arctan(\tan\delta)$, and k is the wavenumber. The wavenumber is defined as $k = \frac{2\pi}{\lambda} = \frac{2\pi\ f}{c_0}$, where λ is the wavelength, f is the frequency and c_0 is the speed of light.

With these simple formulas and a known loss tangent of the material, you can compute the absorbed power in the material. For example, the loss tangent of water (at room temperature) for 60 GHz radiation is about 20. Therefore, a layer of 1 mm of water will absorb $1 - \frac{P(x)}{P(x=0)} = 1 - e^{-\delta k x} = 1 - e^{-\tan^{-1}(20) \cdot \frac{2\pi}{5\,\mathrm{mm}} \cdot 1\,\mathrm{mm}} \approx$ 85 percent of the radiation. In normal radar operation, radar has to pass through the material twice, and the losses will be twice as high. ***Table 2*** illustrates this for the transmission through various materials. The higher the loss tangent is, the higher the losses due to absorption will be. ***Figure 5*** shows the linear dependence in decibels of this loss process over the length for the material zirconia.

Table 2 Reduced transmission due to absorption through various materials at a frequency of 60 GHz (without reflection losses)

Material	Loss tangent	1/e length (mm)	Single-pass transmission through 1 mm (dB)	Double-pass transmission through 1 mm (dB)
HPFS glass	0.0001[4]	7952	$5 \cdot 10^{-7}$	$1.1 \cdot 10^{-6}$
Teflon (PTFE)	0.0004[4]	1988	$2.2 \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$
Zirconia	≈ 0.0013[5]	≈ 612	≈ -0.007	≈ -0.014
Polycarbonate	0.01[4]	80	-0.05	-0.11
ABS	0.02[4]	40	-0.11	-0.22
Poron	0.04[4]	20	-0.22	-0.44
Polyamide-nylon	0.2[4]	4	-1.08	-2.16
Wood at room temperature	up to 0.4[6]	more than 2	≈ -2.08	≈ -4.16
Water at room temperature	≈ 20[7]	≈ 0.5	≈ -8.31	≈ -16.61

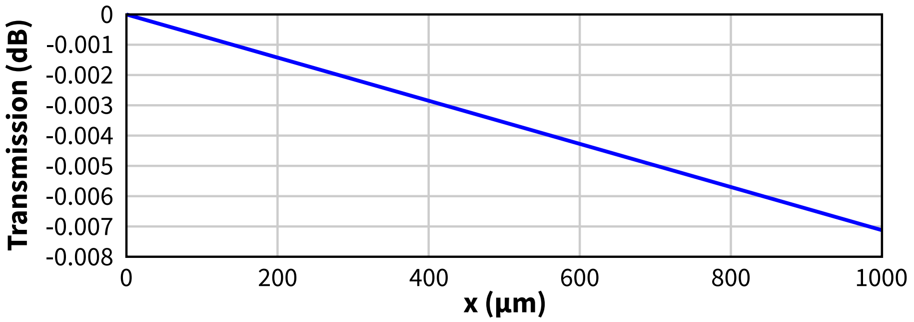

Figure 5 Reduction of transmission in zirconia due to absorption

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[4] Measured at Infineon lab.

[5] Y. Oh, V. Bharambe, B. Mummareddy, J. Martin, J. McKnight, M. A. Abraham, J. M. Walker, K. Rogers, B. Conner, P. Cortes, E. MacDonald, J. J. Adams, "Microwave dielectric properties of zirconia fabricated using NanoParticle Jetting™", Additive Manufacturing, Vol. 27 (2019) p. 586-594

[6] *https://www.microwaves101.com/encyclopedias/miscellaneous-dielectric-constants*

[7] *https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water*

3.3 Skin effect in a conductor

If there is a conductor between the radar sensor and the target, you will need to use skin effect to estimate the losses due to the conductor. Similar to the ***absorption in a dielectric with loss***, skin effect shows an exponential decay over the length in the material.

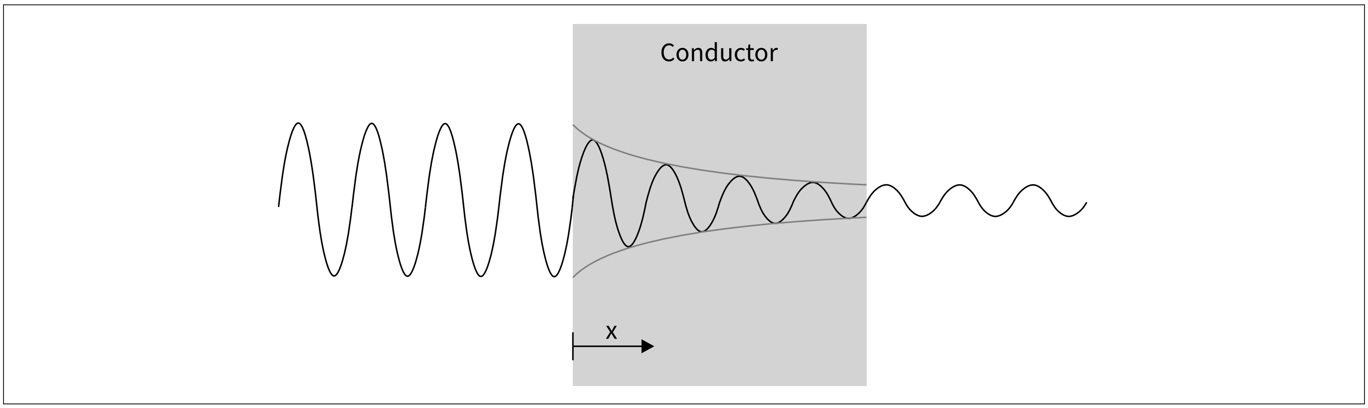

Figure 6 **Illustration of signal attenuation due to skin effect**

Figure 6 shows how radiation is attenuated in a conductor. The magnetic field strength of the radiation decreases exponentially over length. The radiation power is proportional to the squared magnetic field strength.

Magnetic field strength depending on the distance in the conductor:

$$H(x) = H(x=0)\ e^{-\frac{x}{\delta}}$$

Electromagnetic power depending on the distance in the conductor:

$$P(x) = P(x=0)\ e^{-\frac{2x}{\delta}}$$

with the skin depth:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{2}{2\pi f\ \sigma\ \mu_0\mu_r}}$$

Equation 8 **Skin effect**

where ρ is specific resistivity of the conductor, σ is specific conductivity of the conductor, f is the frequency, ω is the angular frequency and μ is the magnetic permeability. With these simple formulas, you can compute the transmitted power through a conductor. ***Table 3*** illustrates this behavior for 60 GHz radiation in various conductors. The results show that even a thin layer of 1 µm results in significant reduction of the transmission. Therefore, even metal foils (more than 10 µm thickness) will hinder any radar operation through them.

Table 3 **Transmission of 60 GHz radiation through various conductors**

Material	Resistivity ρ (µΩ cm)	Skin depth (nm)	Single-pass transmission through 1 µm (dB)	Double-pass transmission through 1 µm (dB)
Silver	1.59[8]	259	-33.5	-67.1
Copper	1.68[8]	266	-32.6	-65.2

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[8] ***https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity***

Table 3 **Transmission of 60 GHz radiation through various conductors (continued)**

Material	Resistivity ρ (µΩ cm)	Skin depth (nm)	Single-pass transmission through 1 µm (dB)	Double-pass transmission through 1 µm (dB)
Gold	2.44[8]	321	-27.1	-54.1
Aluminum	2.65[8]	334	-26	-51.9
Magnesium	4.39[8]	431	-20.2	-40.4
Tungsten	5.6[8]	486	-17.9	-35.7
Iron	9.7[8]	640	-13.6	-27.1
Tin	10.9[8]	678	-12.8	-25.6
Lead	22[8]	964	-9	-18
Titanium	42[8]	1332	-6.5	-13
Stainless steel 304	71.3[9]	1735	-5	-10
Stainless steel 316	77.1[9]	1804	-4.8	-9.6

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[8] *https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity*

[9] T.K. Chu, C.Y. Ho, "Thermal Conductivity and Electrical Resistivity of Eight Selected AISI Stainless Steels", Thermal Conductivity 15 (1978) p. 79-104

4 Far-field and near-field scenarios

It is necessary to distinguish between far-field and near-field applications. In the far-field, the material is far enough away from the radar sensor so that there is no feedback on the antenna behavior. In the near-field, it is necessary to consider such feedback.

Far-field scenario

A far-field scenario is a case in which radar has to penetrate through walls or windows. As buildings cannot easily be modified, it is not usually possible to influence the behavior in these scenarios. But in a known environment, you can compute the expected losses due to walls or windows to estimate the feasibility of a radar use case. In the far-field scenario, you will need to follow only the general considerations, as described in the ***fundamentals***.

Near-field scenario

The near-field scenario is applicable if

$$\text{distance to antenna} < \frac{2D^2}{\lambda}$$

Equation 9 Near-field

where D is the maximum linear dimension of the radar antenna and λ is the wavelength. For a single patch antenna with a ground plane of λ by λ underneath it, the border between near-field and far-field is at 2 λ.

If a material is placed in the near-field of a radar sensor, the material will influence the antenna. This will impact the antenna impedance, which will impact the transmitted and received power. For a detailed analysis of a radome behavior, you should always run full EM-field simulations of the whole system to optimize the radar systems behavior. However, the next section provides simple guidelines for what to do and what to avoid during the radome design process, significantly speeding it up.

5 Radome design guidelines

A radome is a radar sensor enclosure or cover. These covers are typically mounted in the near-field of the radar antenna. When designing radar radomes, you will need to take into account some general considerations in addition to the ***fundamentals***, which are summarized here before discussing concrete examples.

Reflections on dielectrics

To minimize the reflections and maximize the target's signal strength, a dielectric with low permittivity must be selected. Refer to ***Chapter 3.1*** and specifically to ***Table 1*** for details. In addition to that, radome materials that cause low reflections feed back very little to the radar sensor. Fewer reflections from the radome decrease the effect of the radome on the whole radar system.

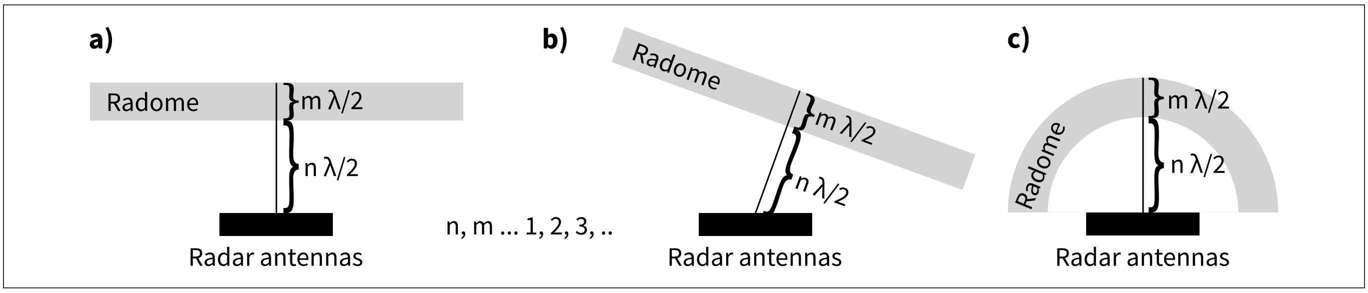

Figure 7 **Back reflections to the antennas are always perpendicular to the radome surface**

In a more detailed analysis, even the exact distance between the radar antennas and the radome matters. Ideally, any surface resulting in direct back reflections to the radar should be at a distance of λ/2 (or a multiple of that), as shown in ***Figure 7***. The reason for this is that in these cases, the radar has to travel λ (or a multiple of that) to get from the radar antenna to the radome surface that has caused the back reflection, and back to the radar antenna. Then, the back reflection will be in phase with the actual emission. This minimizes the effect of the back reflections. In contrast, if the distance is λ/4 (or an odd multiple of that), the back reflections will be perfectly out of phase, and the effect of the back reflections will be maximized. Spherical radomes with the radar antennas in the center (***Figure 7***c) cause back reflections from all possible antenna angles, and thus the effect of the back reflections will be strongest there.

Note: *As described in **Chapter 3.1**, the wavelength in a material is reduced by the refractive index* $\lambda_{\text{material}} = \frac{\lambda_{\text{vacuum}}}{n}$.

Note: *Back reflections cannot cause an effect stronger than the backreflections themselves. Therefore, the correct distance to the radome helps minimize the effect of the radome on the radar antennas, but the effect is significantly weaker than the losses due the back reflections. The received signal strength will be higher for a low permittivity radome at the wrong distance than a high permittivity radome at the correct distance.*

As an example, assume that you want to operate the radar system in the Ultra-Wide Band (UWB) around 60 GHz from 57 to 64 GHz. This bandwidth is more than 10 percent of these values. Therefore, the wavelength of the emitted radar waves varies by more than 10 percent during a chirp, and it is not possible to perfectly align the distance with λ/2 (or multiples of that). One option in this case is to use a thin radome thickness of a few tenths of a millimeter, and place the λ/2 distance (of the center frequency) into the center of the radome. That way both surfaces are close to the minimal back reflection effect, and you can get away with little interaction with the material (= absorption).

Absorption in dielectrics

Absorption in dielectrics is an effect that scales exponentially over the length of the material (***Equation 7***). The material parameter describing the absorption losses is the loss tangent, which is frequency dependent. The loss tangent should be as low as possible to avoid absorption. Refer to ***Table 2*** for details. Furthermore, when designing a radome, consider if it is possible that a water film (or other contamination) might cover the radome. A water film of 1 mm thickness will reduce the signal strength by more than 16 dB.

Conductors

In general, you should avoid using any conducting materials in the radomes. Even thin layers of less than 1 µm can result in attenuations that hinder radar detection (***Table 3***). As an example, consider a plastic case with a metallic coating made of magnesium. To be mechanically stable, the coating needs a thickness of 5 µm. (For simplicity, ignore the effect of reflections on the plastic surfaces and only consider the signal attenuation due to skin effect.) Magnesium has an electrical resistivity of 4.35 µΩ cm, resulting in a skin depth of 428 nm at 60 GHz. The transmission of 60 GHz through 5 µm magnesium is reduced by about 101 dB (for a single pass), hindering any radar operation.

Note: *Even thin metallic coatings or paint that contains metallic particles can significantly reduce radar signal strengths.*

Now imagine that you want to place a radar sensor behind a mirror. Mirrors contain an aluminum layer of about 100 nm. Ignoring, the dielectric reflections on the glass surfaces, the aluminum coating causes an attenuation of about 2.6 dB for a single pass, or 55 percent transmission. Skin effect causes eddy currents in the aluminum, which reflect the radar waves. Some of the remaining 45 percent is lost due to ohmic losses, but the most of this part of the radiation is reflected back (more than 40 percent of the initial power). That will significantly increase the Tx-to-Rx-leakage of the radar system and will thereby influence the radar antenna behavior.

5.1 Curved surfaces and lenses

Curved radome surfaces can lead to various lensing effects. The examples below give an insight into how to design radomes with curved surfaces.

The effect of lenses on radar was covered in ***Chapter 3.1*** (***Figure 2*** and ***Equation 2***). ***Figure 7***c showed the first example of a curved surface. There, the radome is circular or spherical, and the radar antennas are placed in the center; both surfaces are concentric. The RF waves always hit the radome surface perpendicularly. Therefore, there is no diffraction and no lensing effect (sin(0°) = 0 in ***Equation 2***). However, all surfaces reflect the radiation back to the antennas, which will influence the radar antennas. In this case, the backreflections are strong and it is important that the distances of the surfaces are multiples of λ/2.

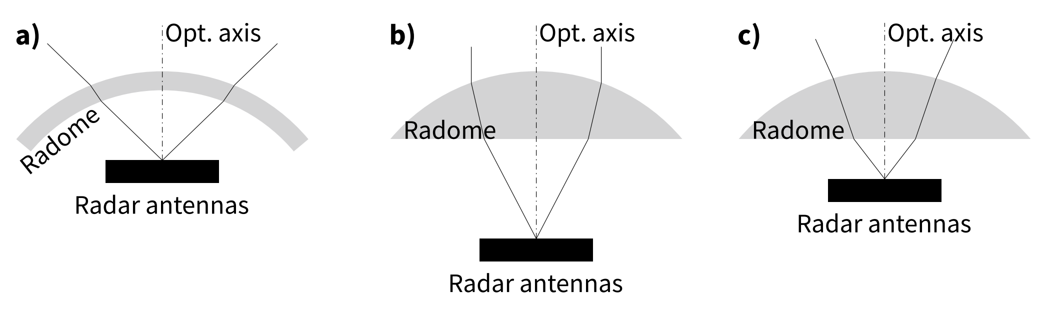

Figure 8 **Three radomes with curved surfaces, and their effects on rays of radar radiation**

Figure 8a shows a similar case. The radome consists of a circular or spherical material, with both surfaces being concentric. The radar antennas are moved along the optical axis away from the concentric center. The resulting radar rays are deflected when entering and leaving the radome. The outgoing and incoming rays are nearly parallel but spatially shifted. The result is that there is almost no lensing effect in this configuration.

In certain applications, lenses can be very useful. An example would be an application that requires a narrow collimated beam that to measure an object across a great distance.

Note: *Lenses alter the direction of the incoming radiation. Therefore, it is recommended to only work with lenses when angle estimation is not required. (Antenna configuration: single Tx and single Rx antenna)*

Figure 8b shows a radome that acts as a lens. One surfaces is curved with radius r_1 and the second surface is curved with radius r_2. (In the case of ***Figure 8***b, one surface is flat. $r_2 \rightarrow \infty$) The radar antennas are in the focal point of the lens. The radar beam after the lens is then collimated. In the collimated beam, the beam power stays constant during propagation. In such a radar system, the target's receiving power only decreases quadratically, not with the fourth power, which increases the radar's maximum detectable distance. To compute the focal length *f* of a thin lens, you can use:

$$\frac{1}{f} = \frac{n_{\mathrm{lens}} - n_{\mathrm{air}}}{n_{\mathrm{air}}}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

Equation 10 **Thin lens**

Figure 8c shows a similar case. The radome consists of a lens and the radar antennas are moved along the optical axis away from the focal point. If the distance between the antennas and the lens is shorter than the focal length, the outgoing beam will remain divergent. In contrast, if the distance between the antennas and the lens is longer than the focal length, the outgoing beam will converge into a single point which is described by

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

Equation 11 **Lens equation**

where *a* is the distance from the antennas to the lens and *b* is the distance from the converged point to the lens.

Note: *Things get much more complicated when the antennas are not positioned along the optical axis. Aberrations will occur, and it is advisable to perform a detailed optical analysis.*

5.2 Polarization and surfaces

A radar system emits a certain polarization. When the radar waves pass through materials, the angle under which a ray of the radar wave hits the surface of the material defines p- and s-polarization for the ray. This behavior is described further in this section.

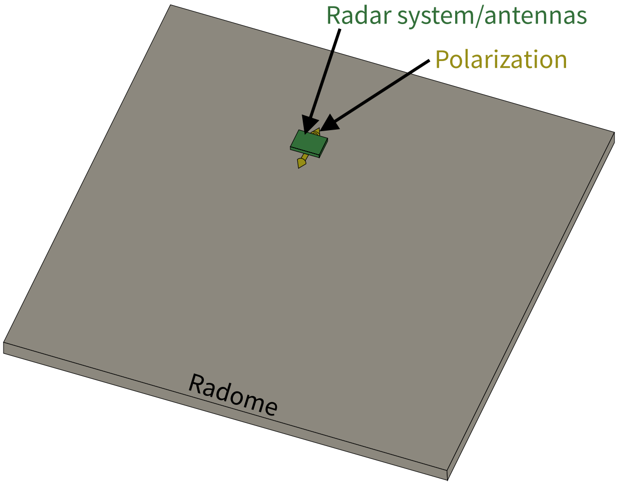

Figure 9 **A radar system in front of a radome parallel to the radar antennas. The arrow denotes the direction of the emitted polarization.**

The example discussed in this section and illustrated in ***Figure 9*** is a radar system in front of a flat radome, for example a casing cover or a window. For simplicity, the surface of the radome is parallel to radar antennas and the polarization of the radar antennas is linear. If you are working with circular polarization, you must decompose the circular polarization into a spatial superposition of two orthogonal linear polarizations.

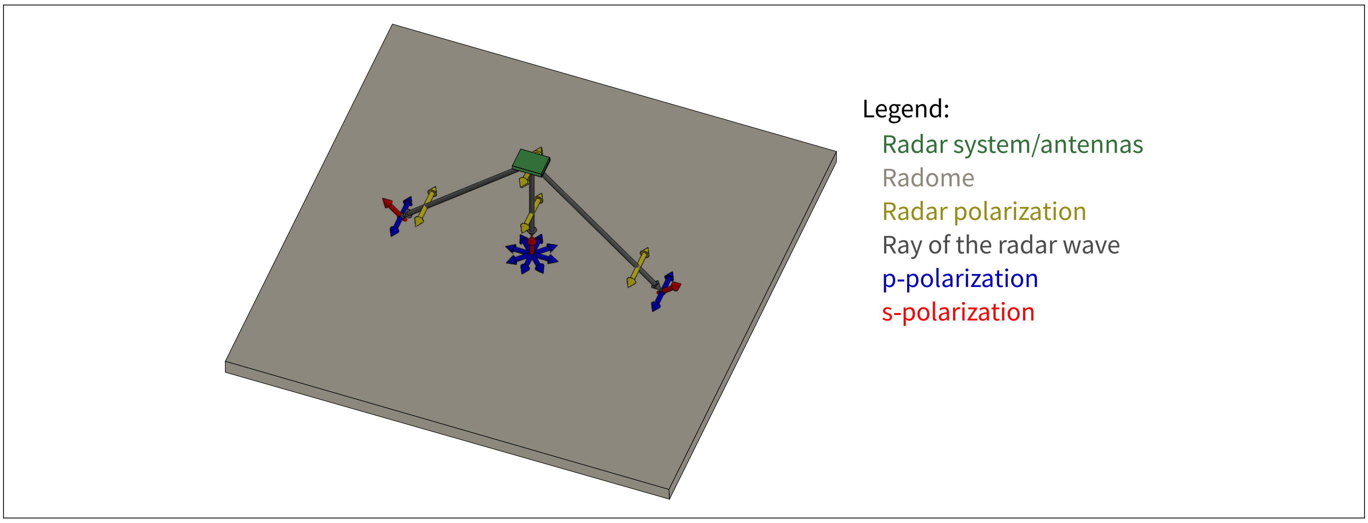

Figure 10 **Three rays of the radar wave with orientation perpendicular to the radar polarization. In this direction, the polarization is purely p-polarization with respect to the radome.**

To analyze the radar wave propagation, consider the emitted radar wave as consisting of many rays, each exiting the radar antennas at a different angle. ***Figure 10*** shows three rays of the radar wave (dark gray arrows). These rays are in a plane perpendicular to the polarization of the radar system (dark yellow arrow). In this plane, the radar polarization always hits the surface of the radome (light gray plane) parallel to the surface. This means that the rays in this plane are p-polarization (blue arrows) for the radome, and the reflected power on the surface can be computed with R_p of ***Equation 3***. For p-polarization, the ratio of transmitted power over incoming power has a local minimum at an angle of 0 degrees (perpendicular to the surface) and it increases up to the Brewster angle, under which reflection is zero (***Figure 3***). Between the Brewster angle and 90 degrees (parallel to the surface), the transmitted power drops down to zero.

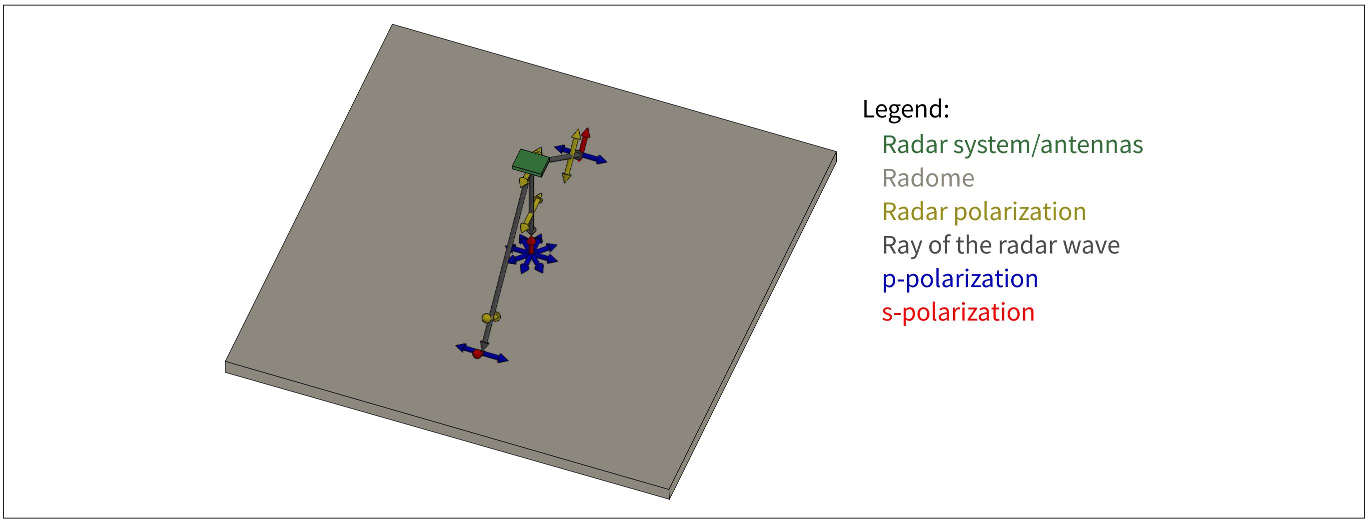

Figure 11 **Three rays of the radar wave with orientation along the radar polarization. In this direction, the polarization is purely s-polarization with respect to the radome.**

Figure 11 shows three rays of the radar wave (dark gray arrows) in a plane parallel to the polarization of the radar system. In this plane, the radar polarization (dark yellow arrow) has no component parallel to the surface of the radome. This means that the rays in this plane are s-polarization (red arrows) for the radome, and the reflected power on the surface can be computed with R_s of ***Equation 3***. For s-polarization, the ratio of transmitted power over incoming power has the maximum at an angle of 0 degrees (perpendicular to the surface), and it drops down to zero at 90 degrees (parallel to the surface) – see ***Figure 3*** for details. The transmission and reflection in this plane will be different than the transmission and reflection in the plane perpendicular to the radar polarization. Therefore, the effect of the radome on the whole radar system in these two directions will differ.

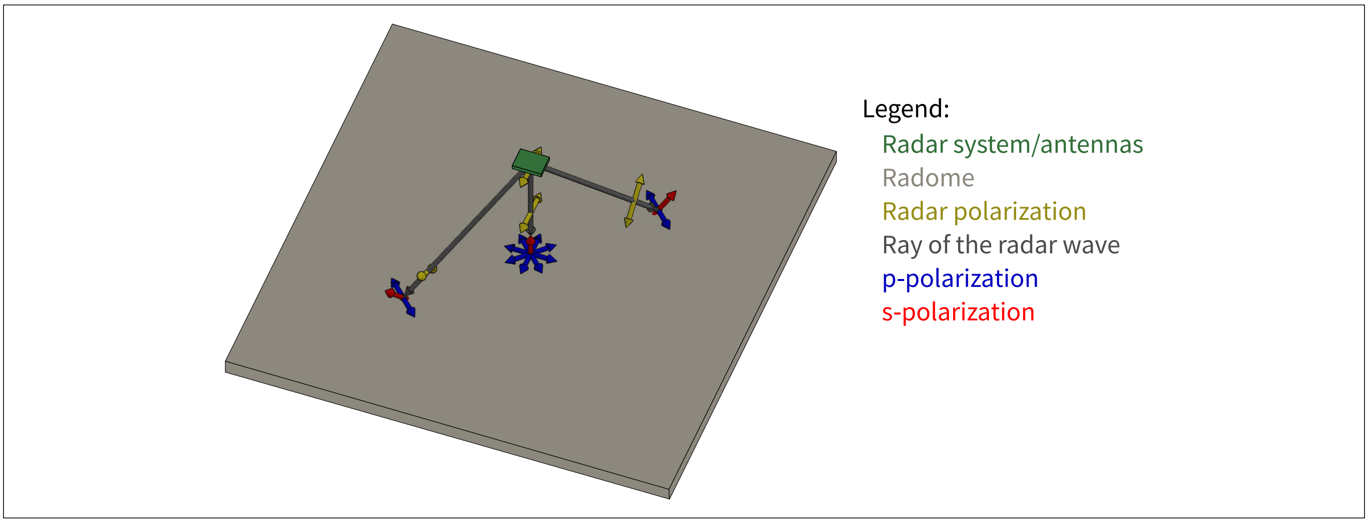

Figure 12 **Three rays of the radar wave with orientation of 45 degrees to the radar polarization. In this direction, the polarization is a mixture of p- and s-polarization with respect to the radome.**

Figure 12 shows three rays of the radar wave (dark gray arrows) under an angle of 45 degrees to the polarization of the radar system. The radar polarization (dark yellow arrow) in this plane is a superposition of p- and s-polarization (blue and red arrows) for the radome. To compute the reflected power on the surface, use R_p and R_s of ***Equation 3***. After transmission through the surface, you can recompose the radar polarization from the p- and s-polarization. As the reflection is different for p- and s-polarization, the polarization after the transmission will be rotated with respect to the incoming polarization. The radar systems have strongly reduced sensitivity for orthogonal polarization and therefore the received signal will decrease even more than by just the reduction of the power due to reflection. This effect is stronger the higher the permittivity of the radome material is.

An example to illustrate the rotation of the polarization is the following. The polarization is described with the electric field $\vec{E}$. You must use the intensity of the emitted radiation $I = \frac{c\,n\,\varepsilon_0}{2}|E|^2$ to get from the electric field to the emitted power $P = I \cdot A$, which is the intensity times and area (or integral over the area). Therefore, the power is proportional to the square of the electric field $P \propto I \propto |E|^2$. Assume that a radar system emits (and receives) vertical linear polarization; of interest are the rays at 45 degrees to the polarization, as illustrated in ***Figure 12***.

Radar polarization:

$$\vec{E}_{\text{radar}} = E_0\left(0 \cdot \vec{E}_H + 1 \cdot \vec{E}_V\right)$$

Radar intensity:

$$I = \frac{c\, n\, \varepsilon_0}{2}\left|E_0 \vec{E}_V\right|^2$$

Radar polarization with the radome surface as the reference

$$\vec{E}_{\text{radar}} = E_0\left(\frac{1}{\sqrt{2}} \cdot \vec{E}_p + \frac{1}{\sqrt{2}} \cdot \vec{E}_s\right)$$

Equation 12 **Incident polarization**

Radar polarization with the radome surface as the reference

$$\vec{E}_{\text{radar}} = E_0\left(\sqrt{R_p} \cdot \frac{1}{\sqrt{2}} \cdot \vec{E}_p + \sqrt{R_s} \cdot \frac{1}{\sqrt{2}} \cdot \vec{E}_s\right) = E_0\left(\frac{\sqrt{R_p} - \sqrt{R_s}}{2} \cdot \vec{E}_H + \frac{\sqrt{R_p} + \sqrt{R_s}}{2} \cdot \vec{E}_V\right)$$

A radar system in the new material only sensitive to vertical polarization would detect

$$I_{\text{vertical}} = \frac{c\, n\, \varepsilon_0}{2} E_0^2 \frac{\left(\sqrt{R_p} + \sqrt{R_s}\right)^2}{4}$$

Equation 13 **Polarization after surface**

After the surface, part of the polarization of the radar is in the horizontal polarization. Therefore, the polarization was rotated by the surface. The bigger the difference between R_p and R_s, the more electric field and power will be in the unwanted horizontal polarization.

Note: *To minimize losses due to the rotation of the radar polarization, use radomes with low permittivity.*

Note: *Radomes will transmit radar waves with different strengths depending on the radar ray's angle. Furthermore, radomes rotate the polarization of the radar in all directions except for the two main axes.*

5.3 Vibrations

Vibrations in the radome are typically undesirable. The effect of a vibrating radome is discussed in this section.

In general, radomes are close to the radar antennas and reflect a fraction of the emitted RF back to the antennas. Because of the close proximity, even weak reflections on the radome surfaces will result in the strongest receiving signal in the radar system. Therefore, radomes affect the Tx-to-Rx-leakage of the radar system.

Vibrations of the radome with respect to the radar antennas change the phase of this strong reflection. Low vibration frequencies are typically no problem. However, if the vibration frequency is in the frequency band of the detected radar signal frequency, the vibrating radome will appear as a ghost target in the radar spectrum at the vibration frequency. As an example, imagine a radar system mounted in a speaker. The surfaces of speakers vibrate with the audio signal they output (up to 20 kHz). If the radar system operates with intermediate frequencies between 500 Hz and 100 kHz, ghost targets with up to 20 kHz will appear in the radar spectrum.

Note: *It is important to minimize the vibrations of the radome with respect to the radar system. Radar systems should be mounted rigidly to casings surrounding them.*

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