

CHARACTERIZING POLYMER MATERIAL PROPERTIES FOR AUTOMOTIVE APPLICATIONS

Automotive radar sensors concealed in bumpers must transmit in the correct frequency domain. To effectively hide sensors, radar-transparent areas usually have the exact same paint as the rest of the vehicle. When selecting paint and coatings for bumpers, you need to know their material properties. In the past, either quasi-optical or waveguide based setups with vector network analyzers (VNA) were used. The following application card describes a simplified material characterization method in the automotive radar frequency domain (76 GHz to 81 GHz) with the R&S®QAR50 automotive radome tester.



Your task

Automotive bumpers typically have several layers: structural base material, primer, paint and a clear coat. The structural base material is usually polypropylene (PP) or poly-carbonate (PC) and gives a bumper its form. The base material often makes up the thickest layer. However, the base layer does not necessarily have the biggest influence on radar signals, since the layer can generally be adapted with various fillers that adjust the layer properties for better UV resistance, rigidity, radar attenuation, etc.

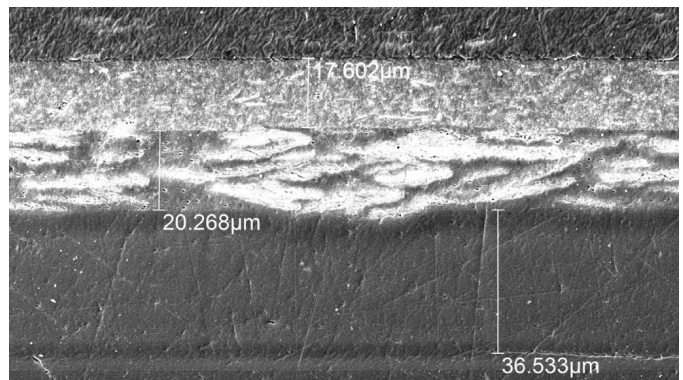
Primer is applied as a second layer to help paint adhere to the base material. The primer layer is typically a couple of micrometers thick. Measuring the thickness of this layer and subsequent ones can involve some uncertainty.

The third layer is paint applied to the primer. The thickness of the paint layer depends on the opacity of the paint and is usually very thin.

To protect paint from environmental influences, a clear coat is applied as the fourth and final layer.

Precise information about the thickness of each layer is needed to estimate its electromagnetic properties. A scanning electron microscope determines the thickness of each layer (see Fig. 1).

Fig. 1: Micrograph showing the different layers of an automotive bumper sample: base material (PP), primer, paint, clear coat (top to bottom).



All layers must be characterized independently. The following description uses four different samples to characterize all four layers:

- ▶ First, just the base material is analyzed
- ▶ Second, the primer is applied to the characterized base material and analyzed
- ▶ The third and fourth steps follow the same logic of applying the next layer to the previous one

The sample must be destroyed to create the microgram. All the measurements above must be made beforehand. The following section examines the required RF analysis of the samples.

Rohde & Schwarz solution

Permittivity estimation with the R&S®QAR50

The permittivity of a sample determines the speed that electromagnetic waves move through a material and how the wave propagation is slowed. Reducing the speed of the electromagnetic wave reduces the wavelength inside the material. With frequency f and speed of light c_0 in a vacuum, the wavelength λ_0 is defined as:

$$\lambda_0 = \frac{c_0}{f}$$

Typical automotive radar frequency:

$$f_{\text{radar}} = 76.5 \text{ GHz, wavelength } \lambda_0 = 3.92 \text{ mm}$$

The wavelength inside a given material with the relative permittivity ϵ_r is calculated as:

$$\lambda' = \frac{c_0}{f\sqrt{\epsilon_r}}$$

Taking the sample polypropylene (PP) sheet with $\epsilon_r \sim 2.5$, the wavelength in the PP sheet is calculated as $\lambda_{PP} = 2.34 \text{ mm}$. Since permittivity reduces the wavelength, it can be calculated using the measured phase if the thickness of the material under test (MUT) is known. The general procedure is demonstrated below.

Calculating the permittivity using relative phase differences

The R&S®QAR50 is normalized to air propagation and every material positioned between the two clusters alters the phase at the receiving antennas. To characterize the sample, we want the phase difference stemming from the MUT within the measurement path.

For reference, the phase Φ in degrees over distance d in free space is calculated as:

$$\phi = \frac{d}{\lambda_0} \cdot 360^\circ = \frac{d}{\frac{c_0}{f}} \cdot 360^\circ$$

The phase Φ' through material of thickness d' is calculated as:

$$\phi' = \frac{d'}{\lambda'} \cdot 360^\circ = \frac{d'}{\frac{c_0}{f\sqrt{\epsilon_r}}} \cdot 360^\circ$$

The $\delta\Phi$ phase change seen by the R&S®QAR50 is the difference between Φ and Φ' and equals:

$$\delta\phi = \frac{d'}{\frac{c_0}{f(\sqrt{\epsilon_r} - 1)}} \cdot 360^\circ$$

With a 2.92 mm PVC sheet and an estimated ϵ_r permittivity of approximately 2.5, the expected phase difference is $\delta\Phi$ or nearly 158°.

Since we are measuring the phase difference $\delta\Phi$ with the R&S®QAR50 and want to calculate permittivity ϵ_r , the formula above must be converted to:

$$\epsilon_r = \left(\frac{(\delta\phi + n \cdot 360^\circ) \cdot c_0}{360^\circ \cdot d' \cdot f} + 1 \right)^2$$

The resulting permittivity is not unique, since the phase difference could unknowingly be multiples of 360°. All possible solutions can be calculated for $n \in \mathbb{N}_0$.

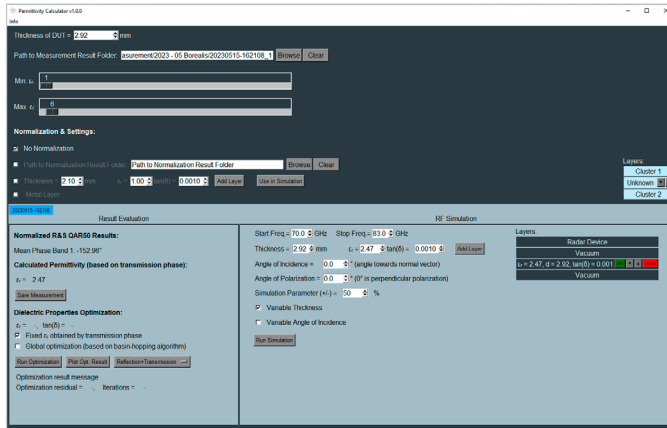
When a sample has multiple layers, all the layers except the one to be determined need to be characterized beforehand. Only then can the known layers be normalized out.

The R&S®QAR50 has software to simplify the calculations. The permittivity calculator utilizes precise phase measurement results from the R&S®QAR50 and can be seen in the example below.

Sample characterization of a painted bumper sample

Using the same set of samples above, the thickness of the different layers is known and plates with individual layers are available for characterization. See Fig. 1 for the thickness of the individual layers.

Fig. 2: The base layer is loaded into the permittivity calculator. The calculated permittivity due to the phase change of 153° at 76.5 GHz is $\epsilon_r = 2.47$.



The base PP plate has a thickness of 2.92 mm for a measured phase difference of around 153° at 76.5 GHz. Using the measurement results as input parameters, the tool calculates an $\epsilon_r = 2.47$ for that specific plate. Fig. 2 shows the result of the calculation in the software.

Using the RF calculation tool described below, the optimal thickness d_{opt} can be derived from the minima for reflection and transmission loss. The reflection minima correlate to the sample resonance frequency and occur at multiples of half the wavelength within the material:

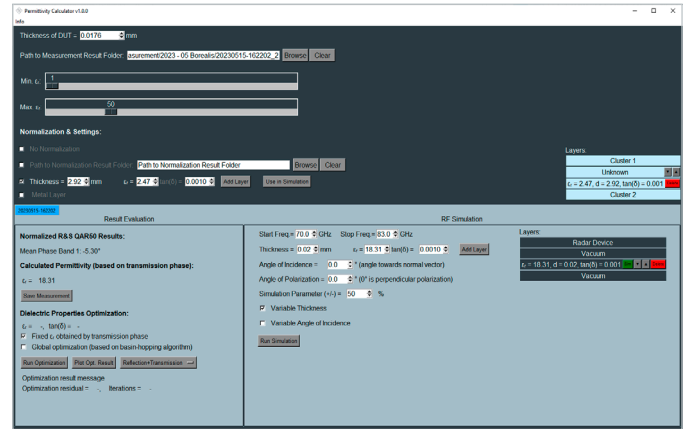
To characterize the remaining layers, the base material must be normalized out. Since its material permittivity is now known, the primer plate can also be normalized.

A normalization layer is added in the software and the next measurement result is loaded.

Normalization can either happen on a previous measurement or by manually adding a layer with a defined thickness and permittivity. In our example, the normalization layer has a thickness of 2.92 mm and $\epsilon_r = 2.47$ is manually added and visualized on the right side of the tool. Based on the measured primer thickness (see Fig. 1) and the measured phase shift of 5.3° from the R&S®QAR50, the estimated permittivity for the primer is $\epsilon_r = 18.3$. The result can be seen in Fig. 3.

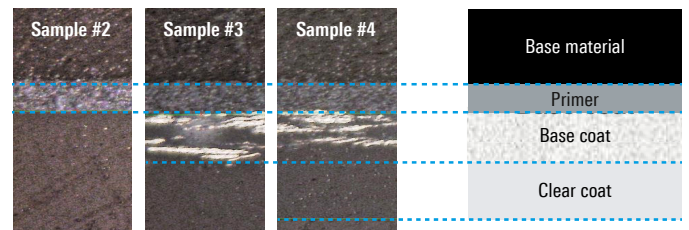
As soon as the second layer is characterized, the remaining layers can be estimated using the steps described above. The characterized layers are added for normalization and the tool calculates the unknown permittivity.

Fig. 3: Adding normalization layers to characterize the primer, paint and clear coat



Since the layer thicknesses across the samples may differ, be careful when adding normalization layers. Fig. 4 shows the micrograph for the samples with an optical microscope. Significant differences in thickness of the paint layer can be spotted for the intermediate sample #3 (to characterize the paint) and sample #4 (to characterize the clear coat).

Fig. 4: Micrograph of the three processed samples showing significant differences in thickness of some layers. Sample #1 (raw PP) is not shown due to the different scaling.



Result evaluation and RF simulation

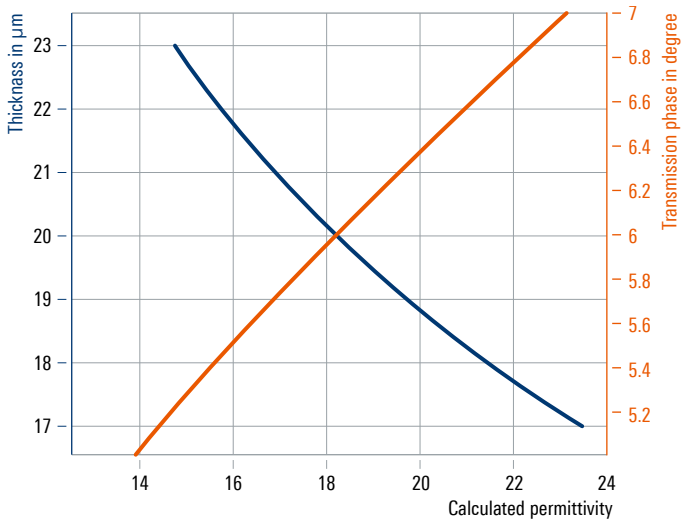
Once a sample is loaded and characterized, the evaluation of the results and RF simulation areas at the bottom of the tool will appear and automatically be filled in with the plate-specific values.

“Read results” shows the mean transmission phase across the selected sample evaluation area as measured by the R&S®QAR50. The transmission phase and thickness of the DUT are entered at the very top, the relative permittivity of the sample is calculated as described above. The R&S®QAR50 precisely measures the transmission phase but the calculated relative permittivity also depends on the accuracy of the thickness measurement.

Measurement inaccuracy influence

Be careful with thickness measurements since both values have an equal influence on the calculated permittivity. Fig. 5 illustrates the impact of inaccurate thickness on transmission phase measurements: A coating with a thickness of $d = 20 \mu\text{m}$ and a resulting phase-shift of $\Delta\varphi = 6^\circ$ results in permittivity with an ϵ_r of approximately 17.8. To illustrate the influence of inaccurate phase and thickness measurements, both parameters are evaluated over typical measurement accuracies: $\pm 3 \mu\text{m}$ for the thickness measurement and $\pm 1^\circ$ for the transmission phase. Fig. 5 shows that the resulting calculated relative permittivity on the x-axis varies tremendously when measurement results become ever more inaccurate. Take care when measuring the RF characteristics of a material and when determining the thickness of the layers.

Fig. 5: Variation of relative permittivity calculation results with deviating thickness measurement and deviating phase measurement results.



The effect revealed previously is less significant for materials with lower permittivity (e.g. PC or PP), which are generally used as a base material in the coating process.

Dielectric property optimization

To simulate material and material stacks and create a virtual duplicate of a radome, the permittivity and the loss factor must be known. The relative permittivity ϵ_r correlates with the compression factor of the wavelength within the material, whereas the $\tan \delta$ (loss factor) characterizes the specific attenuation of a transmitted signal from the layer.

The Rohde&Schwarz permittivity calculator can calculate both parameters and is ideal for radome layer simulations.

The tools for dielectric property estimation are in the lower left corner of the permittivity calculator software. The calculator uses an optimizer that tries to find the best fit between measured and calculated frequency responses based on permittivity and loss factors. Two modes are available:

- ▶ “Fixed ϵ_r obtained by transmission phase” optimizes only $\tan \delta$ while relative permittivity remains fixed
- ▶ Unchecked, the optimizer has more freedom to improve relative permittivity; the relative permittivity calculated from the transmission phase acts as the initial value

Both methods lead to very similar results for most materials. The transmission phase can be measured very accurately and is always a good point to start optimization.

The measured and calculated frequency responses can be plotted after running the optimization for guidance. The “plot Opt. results” function plots the frequency response for the measured material as well as the virtual material using the previously calculated material properties. The operator must check the validity of the results for both methods. Figures 6 and 7 show the generated graphs. Fig. 6 was created using the fixed permittivity from the transmission phase. Fig. 7 was created by optimizing both permittivity and loss tangents for the most suitable frequency response. The material previously measured with the R&S®QAR50 is used to estimate the loss factor.

Fig. 6: Optimization results with fixed permittivity value

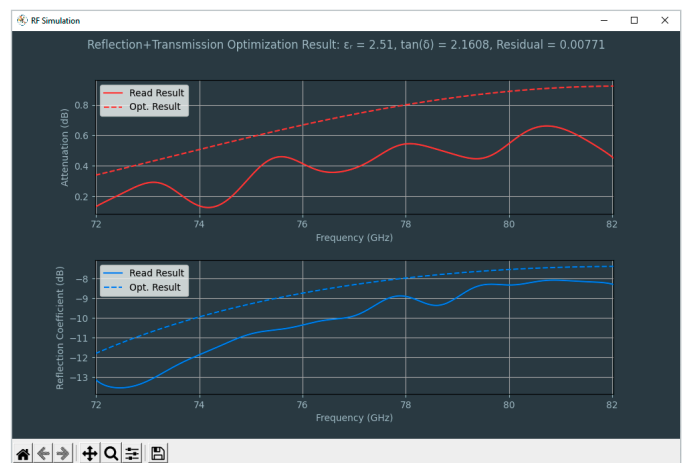
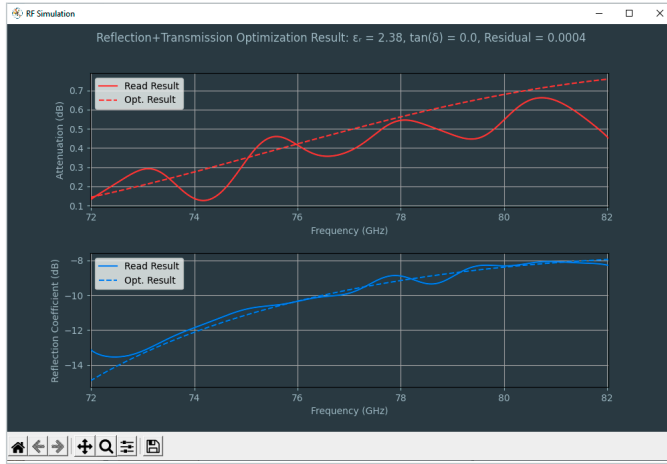


Fig. 7: Optimization results with optimized permittivity and loss factor



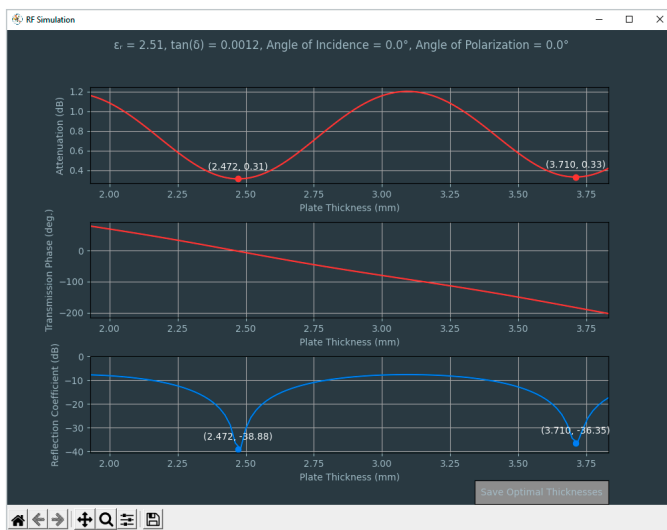
Optimizing both the permittivity and the loss factor are slightly more suitable in our example.

Layer optimization tool

The layer optimization tool on the right side of the permittivity calculator helps simulate multiple layers of paint and evaluate the effect of any differences in layer thickness.

Start and stop frequencies represent the radar band used for the desired application. A digital twin of a part is created using the previously obtained material parameters for a single layer sheet. The “calculate optimal thickness” button can be used for an RF simulation of the layers. The results of the calculation for the sample material and thickness are in Fig. 8.

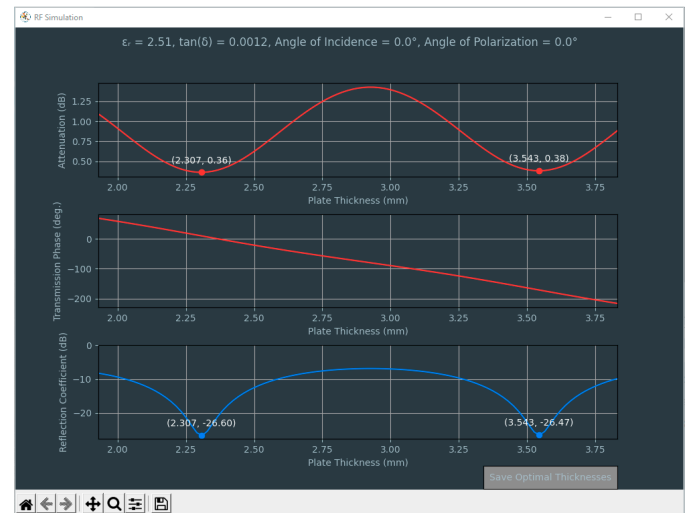
Fig. 8: RF simulation result of a material sheet with $\epsilon_r = 2.51$ and $\tan \delta = 0.0012$



In Fig. 8 the optimal thickness for a single layer sheet is 2.47 mm. This thickness applies to unpainted radar covers. For simplicity's sake, assume that instead of having three layers (primer, paint and coating) a single layer is applied to the base material. The added layer has a thickness of $d = 20 \mu\text{m}$ and an $\epsilon_r = 15$ with a $\tan \delta = 0.02$. The layer represents the typical paint used in the automotive industry.

The challenge is still the same: We want an optimal base material thickness for one layer of paint. After adding the layer to the RF simulation tool, we can perform the same calculations seen in Fig. 8. Assume the thickness of the painting layer is fixed and we want the optimal thickness for the base layer. Fig. 9 shows the RF simulation result.

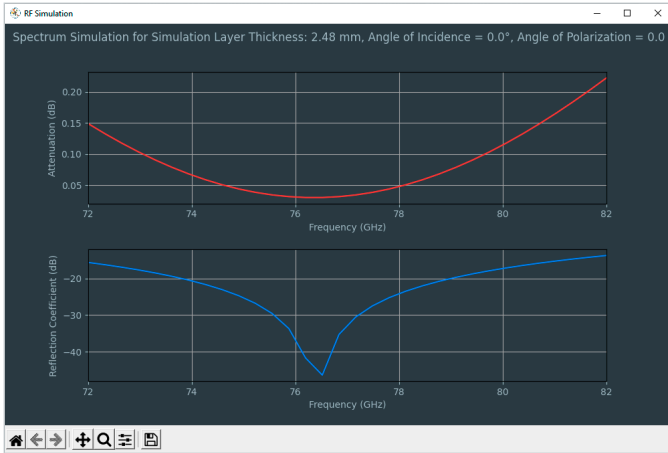
Fig. 9: Simulation of the sheet with an additional layer of paint ($d = 20 \mu\text{m}$, $\epsilon_r = 15$ and $\tan \delta = 0.02$)



Despite the thinness of the layer, its fairly high permittivity can be seen in the simulation. Instead of 2.47 mm for the unpainted sheet, 2.31 mm would be the ideal thickness. The same procedure can be done with all remaining layers and the thickness of the bumper (or other layers) can be optimized.

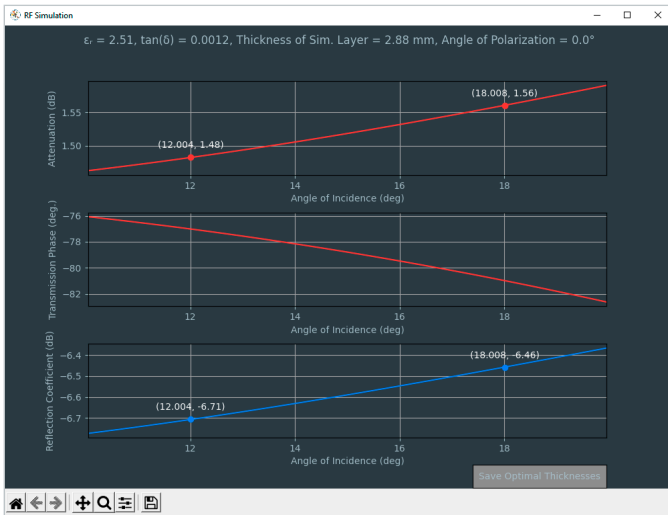
Another useful feature can be activated by hovering over a specific thickness point in the plot and pressing “n”. This will create a frequency resolved plot for that specific thickness.

Fig. 10: Frequency response of a simulated layer with relative permittivity 2.5 and 2.48 mm thickness.



The simulation results described above can be calculated for varying thicknesses and simulation angles. Sticking with a simplified painted sheet, the installation angle of the cover relative to the radar impacts performance. The permittivity calculator software can be used to determine this effect.

Fig. 11: Simulation of typical installation angles of the previously discussed simplified radar cover



Varying the installation angle from 10° to 20° (representing typical automotive installation angles) clearly reveals the effect of the incident angle.

The incidence angle and the polarization of the electric field relative to the incidence angle impact the optimal thickness and optimization. The permittivity calculator can be used to simulate the effects of the polarization angle of the incoming electromagnetic wave. 0° corresponds to a perpendicular polarization between the plane of incidence and the electric field of the incoming electric wave.

Summary

When combined with the R&S®QAR50, the permittivity calculator is the ideal toolchain for over-the-air material characterization. Based on transmission loss, phase and reflection measurements, relative permittivity and the loss factor for the material under test can be calculated. Using the powerful RF simulation tool, the thickness of all layers can be adapted for a well-fitted radome in the automotive radar frequency range.

The permittivity calculator software can be downloaded for free from the R&S®QAR50 website:

www.rohde-schwarz.com/de/software/qar50/

Find a more detailed analysis of the topic together with a comprehensive comparison between the R&S®QAR50 and a vector network analyzer in M. Brinkmann, F. Gumbmann, G. F. Hamberger and B. Simper, "Material Characterization using High-Resolution Multiple-Input Multiple-Output Imaging Radars," 2022 19th European Radar Conference (EuRAD), Milan, Italy, 2022, pp. 229-232.

