Estimation of the relative permittivity from the molecular structure of polymers used in automotive industries

Teresa Bonfigl, Enrico Körner, Jochen Jebramcik, Lothar Kroll, Ilona Rolfes and Jan Barowski

1 Volkswagen AG, Wolfsburg, 38436 Germany
2 Institute of Microwave Systems, Ruhr University Bochum, Bochum 44801 Germany
3 Department of Lightweight Structures and Polymer Technology, Technical University Chemnitz, Chemnitz 09107 Germany and Professor at Opole University of Technology, Opole 45758 Poland

E-mail: teresa.bonfigl@volkswagen.de

Keywords: advanced driver assistance, automotive applications, dielectric measurements, molecule structure, permittivity, radar measurements, radome

Abstract
To scan a vehicle’s environment frequency modulated continuous wave (FMCW) radar sensors are essential. The implementable driver assistance systems based on these sensors increase the comfort of an automobile. When integrating them into the car, the radar sensor’s cover must be taken into account. These parts serve as protection against external chemical and mechanical influences, but they should also support the vehicle design and appearance. Usually, painted polymer components are used as a radome. Depending on their material parameters (i.e. relative permittivity and loss-tangent) polymer covers lead to reflections and absorption, which may impair the radar performance, if they are not properly designed from a microwave point of view. For an appropriate design procedure, the polymer properties, have to be known precisely beforehand or need to be analyzed in realistic experimental configurations. Within this paper it is shown by measurements around the 80 GHz automotive radar bands and calculations based on the polymers repeating unit that the relative permittivity can be estimated from knowledge of the molecule structure. This allows the calculation of the relative permittivity of polymer molecules that have not yet been measured in the W-band at 80 GHz at a very early stage of the design process. Additionally it is shown that it has to be taken into account if the polymer is semi-crystalline or amorphous. Furthermore, the density or crystallinity has to be known.

1. Introduction
The development needed for autonomous driving will require more electronic functions and components to be implemented in future generations of vehicles. In this context, frequency modulated continuous wave (FMCW) radar sensors are particularly important as a key technology to examine the car’s environment. Generally, for most radar sensors within the automotive sector, the frequency range of operation is fixed in the W-band, in the area of 75 to 81 GHz by legal requirements; see [1] and [2]. Due to the wavelength (approx. 3.5 mm) of the electromagnetic waves at this frequency, many materials and components in the sensor’s direct environment are of similar dimensions. Thus they may reveal resonating behavior, which can be an impairment or even an advantage, if the part is designed properly from a microwave point of view. Therefore, the sensor’s interaction with the surrounding materials is a crucial design point and even more important than e.g. in the also used 24 GHz bands.

Additionally, outer skin parts of vehicles usually consist of metal or painted polymers. In this work, the polymer base material is examined in order to create a foundation for paint experiments that can only take place on a substrate. Of course, metallic parts completely reflect the wave of a radar sensor. In the case of polymers, the polymer type, thickness and orientation to the sensor affect the complex interaction of reflection, transmission and absorption. Therefore, given well-defined sensor specifications and material properties (i.e. relative
permittivity and loss tangent), it is possible to design and use even coated polymers for radomes without strongly disturbing the electromagnetic wave; see [3]. It is of special significance to reduce reflections, since a strong reflection by the radome (which is most close to the sensor) will always dominate all other targets that are seen by the radar. Furthermore, this would directly lead to a reduction of achievable measurement range by the energy loss of the wave as well as to a strong disturbance of the radar sensor. A method to reduce reflections by changing the thickness of the part to a certain relative permittivity dependent value is described in [2]. Thus, exact knowledge on the electromagnetic material properties and the opportunity to control the properties during various production steps is of highest importance. However, the relative permittivity given in commercially available polymer datasheets is usually not measured within the W-band but at lower frequencies; see [4] and [5]. Since this parameter is generally frequency dependent, investigations have to be performed at the target frequency range to determine the usability of materials in front of a radar and to design the radome. Therefore, this paper presents a method to estimate the relative permittivity of a material for the GHz frequency range, from the chemical properties of the polymer. Additionally, a W-band FMCW radar (cf. [6]) based measurement method is presented to precisely measure the material parameters in the automotive bands and to validate the analytical method. Section 2 gives an overview on the relevant class of materials. Section 3 describes the radar based measurement apparatus and method. In section 4, the relevant molecular properties are briefly reviewed. The proposed analytic method to estimate the relative permittivity from the molecular properties of a given polymer is introduced in section 5. Furthermore, it presents measurement results and discusses the results of the proposed method. Finally, section 6 concludes the paper.

2. Materials

Plastics make a decisive contribution to reducing vehicle weight; see [7]. Thermoplastics in particular are widely used in vehicles because they are easy and cost-effective to process. The selected polymers for the examination are semi-crystalline and amorphous thermoplastics with an application in the automotive field. Care was taken to ensure that the polymers contain as little additives as possible. In general, therefore, it can be assumed that these are pure polymers. The two lists of the investigated polymers are shown in table 1 (semi-crystalline) and table 2 (amorphous).

The crystallinity of the semi-crystalline polymers is analysed by differential scanning calorimetry measurements (DSC, Netzsch DSC 204 F1 Phoenix; see [8]). The probe was heated from 25 °C–300 °C with a heating rate of 10 K min \(^{-1}\) and the purge gas nitrogen.

The density of the amorphous polymers is determined using the Archimedean principle in water and ethanol.

| Table 1. List of examined semi-crystalline thermoplastics. |
| Semi-crystalline thermoplastics |
| PA6 (Polyamid 6) |
| PBT (Polybutylenterephthalat) |
| PET (Polyethyleneterephthalat) |
| POM C (Polyoxymethylene C) |
| POM Z (Polyoxymethylene Z) |
| PP (Polypropylen) |
| PP EPDM (Ethylten-Propylen-Dien/Polypropylen Blend) |
| PTFE (Polytetrafluorethylen) |

| Table 2. List of examined amorphous thermoplastics. |
| Amorphous thermoplastics |
| PC clear (Polycarbonat) |
| PC ABS (Acrylnitril-Butadien-Styrol/Polypropylen Blend) |
| PET clear (Polyethyleneterephthalat) |
| PMMA (Polymethylenmethacrylat) |
| PVC clear (Polivinylchlorid) |
| SAN (Styrol-Acrylnitril) |
Figure 1. Photograph of the measurement apparatus, showing the radar sensor within a cage system.

Figure 2. Flow chart of the calibration procedure.
3. Radar based material property measurements

The method used for the radar based characterization of the relative permittivity is a free space reflection measurement. Even though resonator [9] or transmission line methods [10] may be of higher precision in material parameter estimations, the free space configuration provides advantages regarding its flexibility and demands on sample geometry; see [11]. It is contact-less, non-destructive, and can handle small samples (in this case diameters in centimeter region). The only assumption is that the material has one or more plane and parallel surfaces. An ultrawideband FMCW radar at 80 GHz (cf. [12]) is utilized as signal transceiver to measure the reflection characteristics. In [13] and [14] the authors have shown how to perform calibrated material measurements with this kind of sensor in the lower THz region. The system considered here offers a bandwidth of 24 GHz from 68 GHz to 92 GHz and thus fits perfectly to the needs within automotive industries. The used measurement apparatus is presented in figure 1.

The photograph shows a commercial cage system yielding the aforementioned radar transceiver with a dielectric lens antenna (see [15]) on the left-hand side. The second element is a plano-convex lens that focuses the transceivers collimated beam onto the sample holder on the right hand side. By using an additional magnetic cage element (bottom left), the material samples can be precisely clamped into the focal plane. A second
magnetic element can be clamped to realize a precise metallic reference target for calibration purposes. In order to ensure precise measurements, a simplified 1-port calibration of the FMCW radar is performed to measure the exact reflection magnitude and phase at the material sample. For this purpose an empty room (or ‘match’) calibration measurement is performed first. Subsequent subtraction of this measurement eliminates all system internal reflections and non-idealities as they may occur from the antenna or additional lenses. To calibrate the reflection magnitude and phase, an additional metallic reflection (or ‘short’) measurement is performed. The metallic target is therefore used for normalization to a reflection magnitude of 1 and a reflection phase of 180°.

Since the considered radar does not offer an Inphase/Quadrature (IQ)-downconverter, its intermediate frequency (IF) signal is a real-valued superposition of many harmonic contributions from reflecting components inside the wave propagation path internal and external to the sensor. The aforementioned calibration procedure is therefore performed after time-gating the signal to the region of interest and subsequent Hilbert-transformation to obtain the complex envelope of the original IF-signal. The signal processing chain is visualized in figure 2 with the material under test (MUT), the chirp-z-transformation (CZT) and the inverse chirp-z-transformation (ICZT).

The raw intermediate frequency (IF)-signals from the radar sensor are shown in figure 3.

Figure 5. Complex envelopes after time-gating and Hilbert-transformation.

Figure 6. Reflection coefficient of the considered PEEK sample alongside a validation curve obtained using literature values $\varepsilon_r = 3.211 - j\cdot0.02$ [17].
With respect to the strong oscillation from the metallic target, the empty room measurement appears almost as a flat line. In the IF signal of the MUT a characteristic envelope behavior resulting from the Fabry–Perot effect inside the material sample is already visible. The corresponding radar echoes are shown in figure 4.

These are obtained by applying an ICZT, which allows to efficiently compute highly resolved echoes without the zero-padding that is needed in fast Fourier transformations (FFT) [16]. Again, the strong reflection of the normalization target is clearly visible. The MUT echo should present two peaks within the region of interest that can be related to the front- and backside reflection. But, due to the small thickness of the sample, they can’t be distinguished very well. After time-gating to the region of interest, a second transformation back into the IF-signal domain is executed. The result is presented in figure 5 and is equivalent to a filtered Hilbert-transformation of the original IF-signals.

In this representation the measurement on the metallic target can directly be used as a normalization and yields information on the pulse shape of the transceiver. Due to the linear relation between ramp-time and instantaneous transmit frequency in FMCW principle, the x-axis of figure 5, representing ADC time, can be substituted by the instantaneous radio frequency (RF) transmit-frequency. Therefore the frequency dependent reflection coefficient of the MUT is directly obtained after normalization. Since our system performs a down-chirp, starting at 92 GHz, the resulting plot in figure 6 is flipped.

Here, a 5 mm thick sample polyether ether ketone (PEEK) is considered. From literature [17] the relative permittivity is expected to be approx. 3, resulting in the modeled curve with a local minimum at 85.4 GHz, which fits very well to the measured one. Finally, the material properties have to be identified from the complex valued, frequency dependent reflection coefficient. For this purpose, several methods are applicable; see [18]. In [13] the authors presented an overview considering the specialties in purely reflection based measures. In this case the model-based curve fitting approach is pursued. For this purpose, the non-linear optimization problem

\[
\mathcal{e}_r, \quad d = \| \mathcal{G}_{\text{meas}} - \mathcal{G}(\mathcal{e}_r, d) \|^2_2
\]

is solved. \(\mathcal{G}_{\text{meas}}\) is the complex-valued measured reflection coefficient according to e.g. Figure 5, whereas the model value \(\mathcal{G}(\mathcal{e}_r, d)\) is derived from the material properties (i.e. complex relative permittivity \(\mathcal{e}_r\) and sample thickness \(d\)) using [19]. Orthogonal incidence on the sample is assumed, which is in-line with the quasi-optical path designed by the configuration. The optimization problem is solved by the iterative Gauss-Newton method. The initial guess for the starting point in the iterative procedure is derived from a stochastic sampling of the cost-function. In figure 7 the measured reflection coefficient is compared to the one obtained from the estimated parameters.

To present the high quality of the curve fit in more detail, especially within the minimum at 85 GHz that yields most information on the dielectric losses, a logarithmic ordinate is chosen. In this case the complex relative permittivity is identified to \(\mathcal{e}_r = 3.18 - i \cdot 0.02\) which is almost identical to the literature value [17]: \(\mathcal{e}_r = 3.211 - i \cdot 0.02\). Furthermore, the material sample thickness is estimated to 4.93 mm. The root-mean-square residual deviation between the modeled and measured curves in figure 7 is 0.11 dB.

![Figure 7. Measured reflection coefficient in comparison to the one obtained from the estimated parameters \(\mathcal{e}_r = 3.18 - i \cdot 0.02\).](image-url)
4. Material theory

As already mentioned, the complex relative permittivity is the material property to describe the interaction of a dielectric material, like a polymer, with the electric field. The real part of the relative permittivity describes the strength of the electric field, that counteracts the field caused by the electromagnetic wave emitted by the radar sensor. Therefore, the field of the wave is weakened within the material and the real part of the relative permittivity shows, how much energy is stored in the material. It depends on the amount of polarisation and electrical conductivity caused by free electrons occurring in the polymer. The two most important polarisation

![Figure 8. Repeating unit of polyvinyl chloride (PVC).](image)

| Table 3. Used electronegativity differences of the bonds calculated from the periodic table. |
|-----------------|-----------------|
| Bond            | ΔEN             |
| C–C             | 0.0             |
| C–H             | 0.4             |
| C–N             | 0.5             |
| C–Cl            | 0.5             |
| O–H             | 0.9             |
| H–Cl            | 0.9             |
| H–N             | 0.9             |
| C–O             | 1.0             |
| C–F             | 1.5             |
| H–F             | 1.9             |

| Table 4. Molar refractivity of bonds [20]. |
|-----------------|-----------------|
| Bond            | \( R_M \) cm³/mol |
| C–H             | 1.68            |
| C–C             | 1.30            |
| C≡N             | 4.17            |
| C≡Cl (terminal) | 5.87            |
| C≡Cl (non-terminal) | 6.24     |
| C–C (aromatic)  | 2.69            |
| C–F             | 1.44            |
| C–Cl            | 6.51            |
| C–Br            | 9.39            |
| C–I             | 14.61           |
| C–O (ether)     | 1.54            |
| C≡O             | 3.32            |
| C–S             | 4.61            |
| C–N             | 1.54            |
| C≡N             | 3.76            |
| C≡N             | 4.82            |
| O–H (alcohol)   | 1.66            |
| O–H (acid)      | 1.80            |
| N–H             | 1.76            |
types for the studied frequency area and polymers are the orientation polarisation and the electronic polarisation. The description can be found in [20] and [21]. The imaginary part of the permittivity describes the dielectric and ohmic losses that are lost in the form of heat. The results presented in this paper only deal with the analysis of the real part of the permittivity. The orientation polarisation of a polymer is based on the polarity of its individual bonds. Polar atomic bonds are chemical bonds in which the atoms involved carry partial charges due to their different electronegativity. In principle, every pairing between atoms stemming from different elements is polar. Generally, the greater the difference between the electronegativities of the atoms, the higher is the polarity of the bond. The used electronegativity differences $\Delta EN$ derived from the periodic table of the elements can be found in table 3.

The molar refractivity $R_M$ yields information about the electronic polarization of atoms by characterizing the arrangements of the electron shells of atoms in molecules. It describes the changes in the properties due to the displacement of the atoms electron shell with respect to its nucleus under the influence of the electric fields of neighbouring atoms. The molar refractivity $R_M \left[ \frac{cm^3}{mol} \right]$ is defined by the Lorenz-Lorentz expression and its value depends on the refractive index $n$, the molar mass $M_W$ and $\rho$ the density.

$$R_M = \frac{n^2 - 1}{n^2 + 2} \times \frac{M_W}{\rho} \tag{2}$$

The molar refractivity of the molecule can be calculated from the individual refractivities of the atoms, see [20]. The molar refractivity values and the values of different bonds can be found in table 4.

5. Proposed method

The aim of this work is to be able to assign the sequence of permittivity values of a composite part made from different polymers to the molecular structure of the respective polymer. Ideally, there is a way to estimate the values from the structure. Such a relation describing the estimation of the relative permittivity at 80 GHz of non-conductive polymers by their molecular structure is shown in the results below. First, a distinction must be made between semi-crystalline and amorphous polymers.

5.1. Semi-crystalline polymers

For semi-crystalline polymers the estimates can be made by using the crystallinity, the average polarity of the atom bindings and the average molar refraction of the atoms in a repeating unit. The values for the semi-crystalline polymer calculations can be found in table 5.

The calculation of the values is carried out here using PVC as an example. The repeating unit of the molecule structure of PVC in figure 8 shows the number and type of bonds.

With this knowledge the average electronegativity ($\Delta EN \text{PVC}$) and average molar refraction ($R_M \text{PVC}$) can be calculated as follows. The bonds present in the repeating unit are:

- C–C: two times; C–H: three times; C–Cl: one.

$$\begin{align*}
\Delta EN_{\text{PVC}} &= \frac{2 \Delta EN_{C-C} + 3 \Delta EN_{C-H} + 1 \Delta EN_{C-Cl}}{6} = 0.283 \\
R_M_{\text{PVC}} &= \frac{2R_M_{C-C} + 3R_M_{C-H} + 1R_M_{C-Cl}}{6} = 2.355
\end{align*} \tag{3, 4}$$

| Polymer | $X_c$ | $\Delta EN$ | $R_M \text{ cm}^3/\text{mol}$ |
|---------|-------|-------------|------------------|
| PA6     | 0.456 | 0.359       | 1.650            |
| PB1     | 0.310 | 0.372       | 1.924            |
| PET     | 0.399 | 0.368       | 1.963            |
| POM C   | 0.767 | 0.581       | 1.592            |
| POM Z   | 0.562 | 0.700       | 1.608            |
| PP      | 0.494 | 0.267       | 1.550            |
| PP EPDM | 0.257 | 0.262       | 1.655            |
| PTFE    | 0.348 | 0.267       | 1.392            |

Table 5. Crystallinity $X_c$, average electronegativity $\Delta EN$ and average molar refraction $R_M$ of the examined semi-crystalline polymers.
For some material the tacticity of the molecule chains can almost equalize the polar character of the bindings. In this case, which applies for the investigated PTFE, the term of the orientation polarization is lower, caused by the presumed average electronegativity $D_{\text{EN}}$ of a C-H bonds instead of C-F bonds. Therefore, it is also important to investigate the chemical linkage to the rest of the molecular chain and the intramolecular ordering or correlation of the segment along the chain. The crystallinity values in table 6 are determined by a Differential Scanning Calorimetry (DSC) analysis.

From these values the following relationship can be found for estimating the relative permittivity of the examined semicrystalline polymers.

$$
\varepsilon_{r,\text{est}} = \frac{X_c \cdot \Delta \text{EN} + R_M - 0.1847}{0.6432}
$$

For some material the tacticity of the molecule chains can almost equalize the polar character of the bindings. In this case, which applies for the investigated PTFE, the term of the orientation polarization is lower, caused by the presumed average electronegativity $\Delta \text{EN}$ of a C-H bonds instead of C-F bonds. Therefore, it is also important to investigate the chemical linkage to the rest of the molecular chain and the intramolecular ordering or correlation of the segment along the chain. The crystallinity values in table 6 are determined by a Differential Scanning Calorimetry (DSC) analysis.

From these values the following relationship can be found for estimating the relative permittivity of the examined semicrystalline polymers.

$$
\varepsilon_{r,\text{est}} = \frac{X_c \cdot \Delta \text{EN} + R_M - 0.1847}{0.6432}
$$

The product of the crystallinity $X_c$ and average electronegativity $\Delta \text{EN}$ could be a description of the orientation polarization of the polymer. The crystalline and therefore ordered areas present in the material effect that the bonds do arrange themselves according to the crystal structure not their polarity. Therefore, there is less polarity compensation between the single bonds. The more ordered structures are present, the higher is the influence of the polarity of the bonds to the permittivity value. The average molar refraction $R_M$ of the atoms in the repeating unit of the polymer is an indicator for the electronic polarization of that material. The influence of the movement of electrons can be neglected due to the low mobility caused by the boundaries of crystalline region in the material. The validity of the estimation is evaluated in figure 9 and table 6, in which the calculated versus the measured relative permittivity is illustrated and the values are presented.

The maximum deviation can be seen for the PA6 polymer with about 13%. In this case the estimate is lower than the measurement, which is presumably caused by water content in the polymer, a factor not considered in this model. PA6 has about 3% of water bound in its structure. With a high water content in the polymer, the
estimate is not valid, since the water increases the permittivity. By implementing the influence of water, the model can be extended in the future. For the other polymers with substantially less water content the maximum deviation is 6% for the PTFE; see table 6. The estimate is therefore reasonably accurate. Furthermore, both measured and calculated values fit very well to literature [22] and [23].

5.2. Amorphous polymers
For amorphous polymers the estimate can be made by using the approximate number of free electrons in a repeating unit $a$, the density $\rho$, the average electronegativity $\Delta EN$ and the average molar refraction of the atoms in a repeating unit $\bar{R}_M$. The values for the amorphous polymer calculations are calculated in the same way as for the semi-crystalline and can be found in table 7.

The material density is measured. The $a$ value is calculated by using the sum of double and triple bonds as well as the Cl-atoms in a repeating unit. The value for a double bond is 2, a triple bond 3 and for an Cl-atom 0.5. For PC and PC ABS the bonds of the interchangeable rest in the repeat unit were neglected. From these values the following relationship can be found for estimating the relative permittivity of the examined amorphous polymers.

$$\varepsilon_{r, est} = \frac{0.1 \cdot a \cdot \rho + \bar{R}_M \cdot \Delta EN + 11.214}{4.5541}$$  \hspace{1cm} (6)

The average molar refraction is again an indicator for the electronic polarization but this time in combination with the average electronegativity. The orientation polarisation has a lower influence, which is caused by the disordered state in amorphous polymers. The polar bonds are randomly distributed. However, the influence of the movement of electrons is higher due to the higher mobility caused by the amorphous structure. The density serves as an indicator for the mobility of the electrons, the number of double bonds as an estimate for the number of moving electrons. The validity of the amorphous estimation is evaluated in figure 10, in which the calculated versus the measured relative permittivity is illustrated.

---

Table 7. Number of double bonds $a$, density $\rho$, average electronegativity $\Delta EN$ and average molar refraction $\bar{R}_M$ of the examined amorphous polymers.

| Polymer       | $a$ | $\rho$ | $\Delta EN$ | $\bar{R}_M$ cm$^2$/mol |
|---------------|-----|--------|-------------|------------------------|
| PC clear      | 4   | 1.200  | 0.303       | 2.026                  |
| PC ABS        | 3.4 | 1.142  | 0.285       | 2.006                  |
| PET clear     | 10  | 1.279  | 0.368       | 1.963                  |
| PMMA          | 2   | 1.196  | 0.413       | 1.666                  |
| PVC clear     | 1.5 | 1.381  | 0.283       | 2.355                  |
| SAN           | 9   | 1.067  | 0.204       | 1.976                  |

---

Figure 10. Verification of the estimation of the relative permittivity by comparing the calculated and measured values of amorphous polymers.
Table 8. Deviation of calculated ($\varepsilon'_r\text{calc}$) and measured ($\varepsilon'_r\text{meas}$) relative permittivity for amorphous polymers.

| Polymer     | $\varepsilon'_r\text{[ - ]}$ | $\varepsilon'_r\text{calc \[ - \]}$ | $\Delta$ [%] |
|-------------|-------------------------------|------------------------------------|-----------|
| PC clear    | 2.71                          | 2.70                               | 0.27      |
| PC ABS      | 2.67                          | 2.67                               | 0.12      |
| PET clear   | 2.90                          | 2.90                               | 0.07      |
| PMMA        | 2.65                          | 2.66                               | 0.60      |
| PVC clear   | 2.67                          | 2.65                               | 0.58      |
| SAN         | 2.76                          | 2.76                               | 0.07      |

The maximum deviation can be seen for the PMMA polymer with about 0.6%; cf. table 8.

The estimate is therefore also reasonably accurate. The results lead to a schematic representation to evaluate a polymer permittivity with the knowledge of its molecule structure of the repeating unit. With the method it can be estimated in advance, without expensive measuring equipment, and it is known whether the polymer is suitable for the application in the 75 to 81 GHz area. Furthermore, the permittivity values can be used to calculate an optimum thickness of the component and therefore to design the component. The influence of water and additional additives would still have to be investigated and implemented in the model. Also, the influence of coloring pigments is very decisive. Additionally, the manufacturing parameters for the injection moulding process, which can be simulated see [24], need to be considered.

6. Conclusion

In this paper the permittivity of polymers in the 75–81 GHz range has been studied. For this purpose, the molecular structure of polymers was analyzed to establish a relationship between the very well documented molecular material properties and the relative permittivity at 80 GHz. Additionally, measurements were carried out in the considered frequency range. With these findings it is now possible to deduce the relative permittivity of polymers from their repeating unit without measurements in the W-band. For polymers that have not been measured in the automotive frequency band yet, the relative permittivity value can, therefore, be estimated with the knowledge on the molecular structure. Also, if some bonds have been replaced in an already measured structure, the electromagnetic material property can be evaluated. Information on these parameters is crucial to precisely predict the radome’s performance. Due to the high relevance of safety aspects in automotive radar, special care must be taken when designing the sensor, the radome, and the integration of both into the chassis. It is shown that a distinction must be made for polymers being amorphous or semi-crystalline. Furthermore, for amorphous polymers the density has to be measured, for semi-crystalline ones the crystallinity has to be known. In the future, additional parameters must be integrated in this mathematical calculation model. This includes the water content, whose influence can be clearly seen with the PA6 measurement, and the content of other additives and pigments. The findings should also be supported by further measurements at other frequencies (see [13]) and a estimation for the loss tangent needs to be found. It is expected that the now empirically determined numerical coefficients in equations (5) and (6) implicitly yield the frequency dependent behavior of the material.

ORCID iDs

Teresa Bonfig © https://orcid.org/0000-0003-4345-5999

References

[1] Ramasubramanian K 2018 Moving from Legacy 24 GHz to State-of-the-Art 77 GHz Radar ATZelektronik worldwide 13 46–49
[2] Pfeiffer F and Biebl E M 2009 Inductive compensation of high-permittivity coatings on automobile long-range radar radomes IEEE Trans. Microwave Theory Techn. (IEEE Transactions on Microwave Theory and Techniques) 57 2627–32
[3] Fitzek F and Raschofer R H 2009 Automotive radome design-reflection reduction of stratified media Antennas Wirel. Propag. Lett. (IEEE Antennas and Wireless Propagation Letters) 8 1076–9
[4] Kilian A, Weinzierl J and Schmidt L 2008 P Permittivity measurement techniques at 24 GHz for automotive polymer composites including thin films and paint foils. German Microwave Conf. (VDE) ed pp 1–4
[5] Hashimoto O, Higashi H, Orikabe K and Ishizaka H 1999 Measurement of complex permittivity of radome material at 60 GHz frequency band Electron. Comm. Jpn. Pt. 1B 82 70–6
[6] Pohl N, Jaschke T, Scherr S, Ayhan S, Pauli M, Zwick T and Musch T 2013 Radar measurements with micrometer accuracy and nanometer stability using an ultra-wideband 80 GHz radar system IEEE Topical Conf. on Wireless Sensors and Sensor Networks (WiSNet) (Austin, TX, United States of America) pp 31–3
[7] Kroll L, Czech A and Wallasch R 2018 Manufacturing and quality assurance of lightweight parts in mass production Journal of Machine Engineering 18 42–56
[8] Drebushchak V A 2004 Calibration coefficient of a heat-flow DSC: I. Relation to the Sensitivity of a thermocouple J. Therm. Anal. Calorim. 76 941–7
[9] Janezic M D and Baker-Jarvis J 1999 Full-wave analysis of a split-cylinder resonator for nondestructive permittivity measurements IEEE Trans. Microwave Theory Techn. 47 2014–20
[10] Baker-Jarvis J, Geyer R G, Grosvenor J H, Janezic M D, Jones C A, Riddle B, Well C M and Krupka J 1998 Dielectric characterization of low-loss materials: a comparison of techniques IEEE Trans. Dielect. Electr. Insul. 5 571–7
[11] Kemptner E and Thurman S 2012 Free space material characterization for microwave frequencies 6th European Conf. on Antennas and Propagation (EuCAP) (Prague, Czech Republic) pp 3513–5
[12] Pohl N, Jaeschke T and Vogt M 2013 An SiGe-chip-based 80 GHz FMCW-radar system with 25 GHz bandwidth for high resolution imaging 14th Int. Radar Symp. (IRS) Dresden ed (Piscataway, NJ) (IEEE) pp 239–44
[13] Barowski J, Zimmernmann M and Rolles I 2018 Millimeter-wave characterization of dielectric materials using calibrated FMCW transceivers IEEE Trans. Microwave Theory Techn. 66 3683–9
[14] Barowski J, Jebramcik J, Alawneh I, Sheikh F, Kaiser T and Rolles I A 2019 Compact measurement setup for in-situ material characterization in the lower THz range Second Int. Workshop on Mobile Terahertz Systems (WMTS) (Bad Neuenahr, Germany) pp 1–5
[15] Schulz C, Baer C, Pohl N, Musch T and Rolles I 2012 A multistatic feeding concept for beam steering based on a dielectric ellipsoidal antenna 6th European Conf. on Antennas and Propagation (EuCAP) (Prague, Czech Republic) pp 286–8
[16] Scherr S, Ayhan S, Fischbach B, Bhutani A, Pauli M and Zwicky T 2013 An efficient frequency and phase estimation algorithm With CRB performance for FMCW radar applications IEEE Trans. Instrum. Meas. 64 1868–75
[17] Schemmel P J and Lambert K M 2019 Refractive index of polyaryletherketone (peek) at X- and W-band NASA/CR-2019-220223 NASA
[18] Baker-Jarvis J, Janezic M and Degroot D 2010 High-frequency dielectric measurements IEEE Instrum. Meas. Mag. 13 24–31
[19] Burns W and Bureger K 1983 High frequency scattering by a thin lossless dielectric slab IEEE Trans. Antennas Propagat. 31 104–10
[20] Blythe A R, Blythe T, Bloor D M and Bloor D 2005 Electrical Properties of Polymers (Cambridge: Cambridge University Press)
[21] Balanis C A 2012 Advanced Engineering Electromagnetics 2nd edn (Hoboken, NJ: Wiley)
[22] Fralick D T 1997 W-band free space permittivity measurement setup for candidate radome materials NASA-CR-201720 NASA
[23] Friedsam G L and Biehl E M 1997 Precision free-space measurements of complex permittivity of polymers in the W-band 1997 IEEE MTT-S Int. Microwave Symp. Digest (Denver, CO, United States of America, 8–13 June 1997) pp 1351–4
[24] Niedziela D, Tröltzsch J, Latz A and Kroll L 2011 On the numerical simulation of injection molding processes with integrated textile fiber reinforcements J. Thermoplast. Compos. Mater. 26 74–90