Characterization of Dielectric Materials by Sparse Signal Processing With Iterative Dictionary Updates

Udaya S. K. P. Miriya Thanthrige\textsuperscript{1,}\textsuperscript{*}, Jan Barowski\textsuperscript{2,}\textsuperscript{**}, Ilona Rolfes\textsuperscript{2,}\textsuperscript{**}, Daniel Erni\textsuperscript{3,}\textsuperscript{**}, Thomas Kaiser\textsuperscript{1,}\textsuperscript{***}, and Aydin Sezgin\textsuperscript{1,}\textsuperscript{***}

\textsuperscript{1}Institute of Digital Communication Systems, Ruhr University Bochum, 44801 Bochum, Germany
\textsuperscript{2}Institute of Microwave Systems, Ruhr University Bochum, 44801 Bochum, Germany
\textsuperscript{3}General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, 47048 Duisburg, Germany

\textsuperscript{*}Student Member, IEEE
\textsuperscript{**}Member, IEEE
\textsuperscript{***}Senior Member, IEEE

Abstract—Estimating parameters and properties of various materials without causing damage to the material under test (MUT) is important in many applications. Thus, in this letter, we address MUT’s parameter estimation by wireless sensing. Here, the precision of the estimation depends on the accurate estimation of the properties of the reflected signal from the MUT (e.g., number of reflections, their amplitudes, and time delays). For a layered MUT, there are multiple reflections, and due to the limited bandwidth at the receiver, these reflections superimpose with each other. Since the number of reflections coming from the MUT is limited, we utilize sparse signal processing (SSP) to decompose the reflected signal. In SSP, a so-called dictionary is required to obtain a sparse representation of the signal. Here, instead of a fixed dictionary, an iterative dictionary-update technique is proposed to improve the estimation of the reflected signal. To validate the proposed method, a vector network analyzer (VNA)-based measurement setup is used. It turns out that the estimated dielectric constants of the MUTs are in close agreement with those reported in literature. Further, the proposed approach outperforms the state-of-the-art model-based curve-fitting approach in thickness estimation.

Index Terms—Sensor signal processing, iterative, dictionary-update, material characterization, sparse signal processing (SSP), thickness estimation.

I. INTRODUCTION

Characterization of materials is important in many areas such as remote sensing, security, and many more. The nondestructive characterization of material is important since it does not cause damage to the material under test (MUT) \cite{1}–\cite{4}. The electromagnetic (EM)-based material characterization methods are mainly categorized into free space, waveguide, and probe methods \cite{3}. In general, reflection mode free-space methods are widely utilized for the nondestructive characterization of material. Because they do not require special requirements regarding the size and the shape of the MUT and also they do not alter the MUT \cite{2}, \cite{3}. The free-space reflection mode measurements can be done in many ways, such as employing a vector network analyzer (VNA) \cite{2} or employing a frequency modulated continuous wave (FMCW) radar \cite{5}–\cite{7}.

The main drawback of the reflection mode is the presence of unwanted multiple reflections \cite{8}. These unwanted reflections are due to the reflections between the front surface of the MUT and the antenna as well as the reflections within the MUT. Due to limited bandwidth at the receiver, the received signals of the reflections are broadened in time and they superimpose with each other. Thus, sophisticated signal processing methods are required to resolve these reflections. Note that the accurate estimation of the amplitudes and phases of the reflections are required to estimate the MUT’s parameters.

The contributions of this letter are summarized as follows. We propose sparse signal processing (SSP) to estimate the properties of the reflected signal from the MUT (e.g., number of reflections, their amplitudes, and time delays). In SSP, a dictionary is required to obtain a sparse representation of the signal \cite{9}. First, we generate a fixed dictionary using time-shifted versions of a reference signal. Second, we propose an iterative dictionary-update algorithm to improve the estimation of the properties of the reflected signal from the MUT. Next, the thickness and the dielectric constant of the MUT are estimated using the properties of the reflected signal. For verification purposes, dielectric constants and thicknesses of Teflon, polyvinylchloride, and acrylic glass are estimated. Furthermore, the proposed method is compared with the state-of-the-art method presented in \cite{10}.

II. MEASUREMENT TECHNIQUE

In this work, a VNA-based free-space reflection mode measurement setup as shown in Fig. 1 is used. Here, the transmitter sends a stepped-frequency continuous wave (SFCW) signal. The reflected signal from the MUT is converted to a fixed intermediate frequency signal $y_I(f)$ by the VNA. There is a one-to-one correspondence between the sampling time and the frequency of the $y_I(f)$ \cite{11}. Therefore, the channel impulse response (CIR) of the MUT is obtained by performing the inverse fast Fourier transform (IFFT) on $y_I(f)$ \cite{11}. For $K$ reflections,
The MUT’s CIR is given by
\[
h(t) = \sum_{k=1}^{K} a_k \delta(t - \tau_k). \tag{1}
\]

The complex signal strength and time delay of the kth reflection are denoted by \(a_k\) and \(\tau_k\), respectively. The frequency (\(f\)) dependent signal strength \(a_k(f)\) mainly depends on the free-space attenuation \(H_f(f)\) and attenuation in the measurement system \(H_s(f)\). Here, a reference measurement is used to estimate the unknown \(H_f(f)\) and \(H_s(f)\). For this, a thin metal plate at the MUT’s position is used. Alternatively, other materials with known reflection coefficient can be used. The metal plate provides a single reflection with the time delay of \(\tau_{m,1}\) and the path gain of \(a_{m,1}(f)\). Thus, the CIR of the metal plate is given by \(h_m(t) = a_{m,1} \delta(t - \tau_{m,1})\). Now, the CIR of the MUT is modeled as a weighted sum of time-shifted CIRs of the metal plate
\[
h(t) = \sum_{k=1}^{K} a_k h_m(t - \bar{\tau}_{m,k}). \tag{2}
\]

Here, \(\bar{\tau}_{m,k}\) is the time delay of the kth reflection of the MUT with respect to the time delay of the metal plate \(\tau_{m,1}\). The relative signal strength of the kth reflection \(a_k(f)\) is given by \(a_k(f)/a_{m,1}(f)\). Now, the dielectric constant of the MUT is estimated as \[\epsilon_f(\bar{\tau}_{m,k})\] using the uniform time grid \(\tau_{m,1}\). The dielectric constant of the MUT is estimated as \[\epsilon_f(\bar{\tau}_{m,k})\] using the uniform time grid \(\tau_{m,1}\). Here, \(\bar{\tau}_{m,k}\) is the time delay of the kth reflection of the MUT with respect to the time delay of the metal plate \(\tau_{m,1}\). The relative signal strength of the kth reflection \(a_k(f)\) is given by \(a_k(f)/a_{m,1}(f)\). Now, the dielectric constant of the MUT is estimated as \[\epsilon_f(\bar{\tau}_{m,k})\] using the uniform time grid \(\tau_{m,1}\).

The estimation of \(\bar{\tau}_{m,k}\) is formulated as \[l_1\]-norm minimization problem
\[
\min_{\bar{\tau}_{m,k}} \|\bar{\tau}_{m,k}\|_1 \quad \text{s.t.} \quad \|h - D\bar{\tau}\|_2^2 \leq \beta. \tag{7}
\]

Note that the fixed dictionary \(D_f \in \mathbb{C}^{L \times G}\) is generated based on the uniform time grid \(\tau\). Our objective is to update the fixed dictionary \(D_f\) by adjusting \(\tau\). Afterward, the iterative dictionary-update algorithm alternates between the following steps until we achieve desired convergence criteria \((\|h - D\bar{a}\|_2^2 \leq \beta)\) or the maximum number of iterations is reached.

1. Step 1: Update \(\bar{a}\) while keeping the dictionary \(D\) fixed.

Let \(\bar{a} = [\bar{a}_1, \ldots, \bar{a}_G]^T\). Since there are only \(K\) reflections, the vector \(\bar{a} \in \mathbb{C}^G\) only has \(K\) nonzero elements. Let the discrete-time CIRs of the MUT and the metal plate are given by \(h\) and \(h_{m,k}\) \(\in \mathbb{C}^L\), respectively. Now, the dictionary \(D_f \in \mathbb{C}^{L \times G}\) is reformulated as
\[
D_f = [h_{m,1}, \ldots, h_{m,k}, \ldots, h_{m,G}]. \tag{5}
\]

Note that the fixed dictionary \(D_f\) in Section IIIA is generated based on the uniform time grid \(\tau\). Our objective is to update the fixed dictionary \(D_f\) by adjusting \(\tau\). Afterward, the iterative dictionary-update algorithm alternates between the following steps.

1. Step 1: Update \(\bar{a}\) while keeping the dictionary \(D\) fixed.

Let \(\bar{a} = [\bar{a}_1, \ldots, \bar{a}_G]^T\). Since there are only \(K\) reflections, the vector \(\bar{a} \in \mathbb{C}^G\) only has \(K\) nonzero elements. Let the discrete-time CIRs of the MUT and the metal plate are given by \(h\) and \(h_{m,k}\) \(\in \mathbb{C}^L\), respectively. Now, the dictionary \(D_f \in \mathbb{C}^{L \times G}\), which contains \(G\) time-shifted CIRs of the metal plate, is given as
\[
D_f = [h_{m,1}, \ldots, h_{m,k}, \ldots, h_{m,G}]. \tag{5}
\]

Note that \(k\)-th column of the dictionary \(D_f\) is given by \(h_{m,k}\) and \(h_{m,k}\) is the CIR of the metal plate corresponds to the time delay \(\bar{\tau}_{m,k}\). To this end, the discrete-time version of (4) is given as
\[
h = D_f \bar{a}. \tag{6}
\]

The estimation of \(\bar{a}\) is formulated as \[l_1\]-norm minimization problem
\[
\min_{\bar{a}} \|\bar{a}\|_1 \quad \text{s.t.} \quad \|h - D\bar{a}\|_2^2 \leq \beta. \tag{7}
\]

Here, \(\beta\) is the error tolerance. In this letter, the orthogonal matching pursuit (OMP) [13] is used to estimate \(\bar{a}\) in (7). In the following, we refer to this method as \[l_1\]-norm minimization-based fixed dictionary approach (FD). Note that, we cannot guarantee that the time delays of the reflections of the MUT are exactly matched with the grid points of the time grid \(\tau\). This leads to a grid mismatch. To solve this, we propose an iterative dictionary-update algorithm as discussed next.

B. Iterative Dictionary-Update Algorithm

Note that the fixed dictionary \(D_f\) in Section IIIA is generated based on the uniform time grid \(\tau\). Our objective is to update the fixed dictionary \(D_f\) by adjusting \(\tau\). Note that after the update, the time grid \(\tau\) is no longer a uniform grid. Let \(D \in \mathbb{C}^{L \times G}\) be the updated dictionary. This dictionary update process is given in algorithm 1. The algorithm 1 is initialized by setting \(D = D_f\). Afterward, the iterative dictionary-update algorithm alternates between the following steps.

1. Step 1: Update \(\bar{a}\) while keeping the dictionary \(D\) fixed.
2) Step 2: Update the dictionary $D$ while keeping $\bar{a}$ fixed.

In the first step, the OMP algorithm is used to estimate $\bar{a}$. Let $s_0$ be the number of nonzero elements in $\bar{a}$. Note that the OMP algorithm utilizes the correlation between the input $h$ and the columns of $D$ to obtain the nonzero elements in $\bar{a}$. Motivated by this, in the second step, the correlation between the input $h$ and the columns of $D$ is used to update the dictionary. It is worth noting that, only the columns of the dictionary which correspond to the nonzero elements in $\bar{a}$ are updated. We refer to this method as $l^1-$norm minimization-based iterative dictionary-update approach ($DU$).

To have a fair comparison with the $FD$ and $DU$, we estimate $a$ using the $l^2$-norm minimization as given below. This method is referred to as $l^2-$norm minimization approach ($l^2 NM$)

$$\min_{\bar{a}} \|\bar{a}\|_2^2$$

s.t. $\|h - D\bar{a}\|_2^2 \leq \beta$.  \hspace{1cm} (8)

IV. MEASUREMENT SETUP AND RESULTS

For verification purposes, various materials with different thicknesses as listed in Table 2 were tested. Actual thicknesses of the MUT’s and measured frequency range are listed in the first column of Table 2. The measurement setup based on the VNA as shown in Fig. 1 was used as the experimental setup. The bandwidth, antenna gain, frequency step, and RF filter bandwidth of the measurement setup are 35 GHz, 15 dBi, 17 MHz, and 1 kHz, respectively. A parabolic mirror with a diameter of 4 in was used in the measurement setup. The distance from the mirror to the MUT is 10 cm. First, the MUT was placed in the sample holder to measure the reflected signal from the MUT. Next, the metal plate was placed in the sample holder to measure the reference measurement. Here, the IFFT was used to obtain the CIRs of the MUT and the metal plate. Next, SSP-based approaches given in Section III were used to estimate $\bar{a}$ of the MUT. Afterward, the dielectric constant of the MUT was estimated using (3). In this step, $s_0$, the number of nonzero elements in $\bar{a}$ was changed from 2 to 8 with the step size of 1 and the $s_0$ value which provides the lowest error ($\|h - D\bar{a}\|_2^2$) was selected. Also, the time grid $r$ of the fixed dictionary $D_f$ has an impact on the performance. Therefore, we select a time grid from different uniform time grids which has the lowest reconstruction error ($\|h - D_r\bar{a}\|_2^2$). The error tolerance $\beta$ was set as $10^{-2}$.

A. Decomposition of the Received Signal From MUT

The decomposition of the reflected signal from the MUT by the $l^1$ and the $l^2$-norm minimization approaches is analyzed here. Fig. 2(a) and (b) show the decomposition of the reflected signal of the PMMA sample with 3.3-mm thickness by using the proposed $DU$ and $l^2 NM$ approaches, respectively. The amplitudes and the time delays of the estimated reflections by these methods are indicated as vertical lines in Fig. 2. Further, the corresponding time delays of the reflections which are shown in Fig. 2 are listed in Table 1. The first and the second dominant reflections which are shown in Fig. 2 correspond to the front and the backside reflections of the MUT. The remaining reflections correspond to the multiple reflections. It can be seen that the $l^2 NM$ estimates more reflections when compared to the $DU$. Note that, the time delays of the internal reflections of the MUT should be integer multiples of the timedelay between the first and the second dominant reflections.

Most of the time delays of the recovered reflections by the $DU$ satisfy this property [e.g., fourth, fifth, and sixth reflections shown in Fig. 2(a)]. However, in the $l^2 NM$, this is not the case. Thus, the proposed $DU$ is able to recover internal reflections inside the MUT better than the $l^2 NM$. Further, the $l^2 NM$ does not accurately estimate the actual number of reflections. Hence, the estimation accuracies of the first and the second dominant reflections by the $l^2 NM$ decrease. Thus, it can be concluded that the $l^1-$norm minimization performs much better compared to the $l^2-$norm minimization.

B. Dielectric Constants and Thicknesses Estimation

For comparison, the dielectric constants and thicknesses of the MUTs were estimated by the model-based curve-fitting approach ($CF$) presented in [10] and the $l^2-$norm minimization ($l^2 NM$). Here, the loss factor ($\tan\delta$) of the MUT is calculated by $\varepsilon_r(f) = \varepsilon_r(1 - \tan\delta)$. Table 2 shows the comparison of the dielectric constants and thicknesses that are estimated by the proposed $DU$ and other approaches ($FD$, $l^2 NM$, and $CF$). As given in Table 2, the estimated dielectric constants by the $l^1-$norm minimization ($DU$ and $FD$) and the $l^2-$norm minimization ($l^2 NM$) show close agreement for the thin MUTs. However, for thick samples, the estimated dielectric constants by the $l^2-$norm minimization show higher deviations compared to the values reported in the literature. This is due to the fact that, as sample thickness increases EM waves travel more distance inside the sample in internal reflections. Thus, for a thin sample, losses inside the sample are smaller compared to a thick sample. Therefore, for a thin sample, we could expect more internal reflections than for a thick sample. Thus, the reflected signal of a thin sample is less sparse compared to a thick sample. Due to this, the $l^2-$norm minimization provides less accurate

| MUT      | Method | $\varepsilon_r(f)$ | Loss factor | Estimated thickness (mm) | Estimation error % |
|----------|--------|---------------------|-------------|--------------------------|-------------------|
| Acrylic glass | FD     | 2.5920              | 0.0048      | 3.1367                   | 4.95              |
| (PMMA)   | DU     | 2.5990              | 0.0044      | 3.2099                   | 2.73              |
| 3.30 mm  | $l^2 NM$ | 2.6095              | 0.0351      | 3.0953                   | 6.21              |
| (75-110 GHz) | CF     | 2.6132              | 0.0262      | 3.1780                   | 3.70              |
| PVC      | FD     | 2.7602              | 0.1797      | 15.1980                  | 3.58              |
| 15.76 mm | DU     | 2.7240              | 0.1784      | 15.2955                  | 2.95              |
| (75-110 GHz) | $l^2 NM$ | 2.5989              | 0.1708      | 15.4910                  | 1.71              |
| CF       | 2.8895 | 0.0299              | 14.8620     | 5.70                     |
| Teflon (PTFE) | FD     | 2.0006              | 0.0408      | 20.4300                  | 0.64              |
| 20.30 mm | DU     | 2.0015              | 0.0406      | 20.4217                  | 0.60              |
| (75-110 GHz) | $l^2 NM$ | 1.8023              | 0.3768      | 22.1100                  | 8.91              |
| CF       | 2.0582 | 0.0030              | 20.0940     | 1.01                     |
Table 3. Comparison of the Estimated Dielectric Constants by the Proposed Approach (DU) With the Literature.

| MUT          | \(\varepsilon_r(f)\) by the DU (\(\log_{10}\)) | \(\varepsilon_r(f)\) From literature (\(\log_{10}\)) | Loss factor DU | Loss factor literature |
|--------------|---------------------------------------------|--------------------------------------------------|----------------|-----------------------|
| PMMA         | 2.59                                       | 2.58–2.60 [14]                                     | 4.03 x 10^-1  | 6.0 x 10^-1 [14]     |
| PVC          | 2.72                                       | 2.78 [15], 2.88 [16]                               | 1.78 x 10^{-1} | 1.4 x 10^{-1} [17]   |
| Teflon       | 2.00                                       | 2.03 [14], 2.02–2.04 [18]                           | 4.06 x 10^{-2} | 5.3 x 10^{-1} [14]   |

results compared to the \(l^1\) —norm minimization-based methods (DU and FD) for thick samples.

Note that the \(l^1\) —norm minimization-based methods (DU and FD) show close agreement with the dielectric constants which are estimated by the state-of-the-art CF approach and the dielectric constants given in the literature (as shown in Table 3) for all samples.

Here, a discussion on the thickness estimation of the MUTs is due. As given in Table 2, the proposed DU approach provides the lowest thickness estimation error for the majority of samples (two out of three samples). For the other sample (PVC), the DU provides the second-best thickness estimation with 1.2% difference from the best. This is due to the fact, that the CIR of the PVC is less sparse compared to the other two MUTs (PTFE and PMMA). Moreover, by comparing the thickness estimation error between DU and FD, it can be observed that the iterative dictionary-update approach improves the thickness estimation. Here, the improvements are 2.22, 0.63, and 0.04% for the MUTs given in Table 2, respectively. Although the thickness estimation improvements from the FD to the DU are small in numbers, the DU is the best thickness estimator for two out of three MUTs. Further, the FD is not the best thickness estimator for any MUT given in Table 2. Therefore, it is worth to consider the iterative dictionary-updates rather than a fixed dictionary. Finally, we shortly discuss the processing times of the algorithms. For a single MUT, the processing times needed to complete the FD, DU, and CF in Matlab computing environment are 1.58, 5.76, and 4.8 s, respectively. The processing time of the DU is in a similar range as the CF and slightly higher than the FD.

V. CONCLUSION

In this letter, we investigate the material characterization in free-space reflection mode. SSP-based signal decomposition with iterative-dictionary update was used to estimate the dielectric constant and the thickness of the MUT. The results show good agreement with the dielectric constants of the tested materials which are reported in the literature. Also, the thickness estimation error of the proposed method DU was always less than 2.95% for the cases considered. Further, the iterative dictionary-update improves thickness estimation compared to a fixed dictionary-based approach. In comparison, the \(l^1\)—norm minimization approach are performing better compared to the \(l^2\)—norm minimization approach.

ACKNOWLEDGMENT

This work was supported by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)-Project-ID 287022738-TRR 196 (S02 and M0204 Projects). They would also like to thank Y. Zantah and B. Sievert for taking the VNA-based measurements. They would also like to thank J. Jebramcik and O. Garten for their valuable discussions.

REFERENCES

[1] D. Wen, M. Fan, B. Cao, B. Ye, and G. Tian, “Lift-off point of intersection in spectral pulsed eddy current signals for thickness measurement,” IEEE Sensors Lett., vol. 2, no. 2, Jun. 2018, Art. no. 700104.
[2] J. Barowski, T. Schulzle, I. Willms, and I. Rolfs, “Monostatic and thickness-independent material characterisation based on microwave ellipsometry,” in Proc. IEEE German Microw. Conf., 2016, pp. 449–452.
[3] R. A. Fenner, E. J. Rothwell, L. L. Frasch, and J. L. Frasch, “Characterization of conductor-backed dielectric materials with genetic algorithms and free space methods,” IEEE Microw. Wireless Components Lett., vol. 26, no. 6, pp. 461–463, Jun. 2016.
[4] B. Jamali, D. Ramalingam, and A. Babakhani, “Intelligent material classification and identification using a broadband millimeter-wave frequency comb receiver,” IEEE Sensors Lett., vol. 4, no. 7, Jul. 2020, Art. no. 3501104.
[5] B. Friederich, T. Schultzle, and I. Willms, “A novel approach for material characterization based on a retroreflector wide band transceiver radar,” in Proc. Int. Conf. Ubiquitous Wireless Broadband, Oct. 2015, pp. 1–4.
[6] J. Jebramcik, I. Rolfs, N. Pohl, and J. Barowski, “Millimeterwave radar systems for in-line thickness monitoring in pipe extrusion production lines,” IEEE Sensors Lett., vol. 4, no. 5, May 2020, Art. no. 6000504.
[7] J. Weiß and A. Santra, “One-shot learning for robust material classification using millimeter-wave radar system,” IEEE Sensors Lett., vol. 2, no. 4, Dec. 2018, Art. no. 7001504.
[8] K. Haddadi, M. M. Wang, O. Benzaim, D. Gay, and T. Lasti, “Contactless microwave technique based on a spread-loss model for dielectric materials characterization,” IEEE Microw. Wireless Components Lett., vol. 19, no. 1, pp. 33–35, Jan. 2009.
[9] M. Aharon, M. Eldad, and A. Bruckstein, “K-SVD: An algorithm for designing overcomplete dictionaries for sparse representation,” IEEE Trans. Signal Process., vol. 54, no. 11, pp. 4311–4322, Nov. 2006.
[10] J. Barowski, J. Jebramcik, I. Alawneh, F. Sheikh, T. Kaiser, and I. Rolfs, “A compact measurement setup for in-situ material characterization in the lower THz range,” in Proc. Int. Workshop Mobile Terahertz Syst., Jul. 2019, pp. 1–5.
[11] Z. Zhang, Y. Nian, J. Chen, and M. He, “An experimental study to optimize the stepped-frequency continuous-wave radar parameters for noncontact multi-target vital sign monitoring,” in Proc. IEEE Int. Conf. Comput. Electromagn., 2019, pp. 1–4.
[12] S. Vogt, O. Garten, J. Jebramcik, J. Barowski, and I. Rolfs, “Asymptotic simulation methods as forward models in multilayer material characterization applications,” in Proc. IEEE MTT-S Int. Microw. Workshop Series Adv. Materials Processes RF THz Appl., 2019, pp. 109–111.
[13] Y. C. Pati, R. Rezaifar, and P. S. Krishnaprasad, “Orthogonal matching pursuit: recursive function approximation with applications to wavelet decomposition,” in Proc. 27th Asilomar Conf. Signals, Syst. Comput., vol. 1, 1993, pp. 40–44.
[14] J. Jebramcik, J. Barowski, and I. Rolfs, “Characterization of layered dielectric materials using ultra-wideband FMCW-radar measurements,” in Proc. Asia-Pacific Microwave Conf., Nov. 2018, pp. 1327–1329.
[15] G. L. Friedsam and E. M. Biebl, “Precision free-space measurements of complex permittivity of polymers in the W-band,” in Proc. IEEE MTT-S Int. Microw. Symp. Dig., vol. 3, Jun. 1997, pp. 1351–1354.
[16] A. Kazemipour et al., “Design and calibration of a compact quasi-optical system for material characterization in millimeter/submillimeter wave domain,” IEEE Trans. Instrum. Meas., vol. 64, no. 6, pp. 1438–1445, Jun. 2015.
[17] J. Barowski, M. Zimmermann, and I. Rolfs, “Millimeter-wave characterization of dielectric materials using calibrated FMCW transceivers,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 8, pp. 3683–3689, Aug. 2018.
[18] T. Ozturk, M. Hudlicka, and I. Ulaer, “Development of measurement and extraction technique of complex permittivity using transmission parameter S 21 for millimeter wave frequencies,” J. Infrared Millimeter, Terahertz Waves, vol. 38, no. 12, pp. 1510–1520, 2017.