Investigations of the Impact of Extinguishing Water on Sub-THz Material Characteristics

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Abstract
In this paper an ultra-wideband system is used to examine the effect of extinguishing water on a multilayer reflection concept. Additionally, the reflection measurements of typical indoor-materials with different water contents will be compared with the analytical results.

The drawbacks of common characterization techniques, which require a multiple change in the measurement setup by sweeping the angle of incidence or supply just a narrow-band analysis are avoided. Furthermore, the reflection theory of multi-layer objects is briefly described so that the theoretical results are compared with real measurement. By the comparison of the measurement and the simulation a validation of this model is possible as well.

The experimental validations are performed with two dielectric test objects. For the measurements the ZVB-20 network analyzer of Rohde & Schwarz is used for the analysis from 4.5 GHz to 13.5 GHz.

Keywords:

Introduction
Material characterization techniques in hostile and hazardous scenarios are a challenging issue in security applications. Hence, it is not only an interesting field for the academic research, but also of great interest for e.g. fire brigades and disaster relief teams.

The encountered fog and dust pollution of emergency scenarios limit the usage of classical optical sensors as the radiation is highly damped. To overcome this, usually ultrasound sensors are used, but these are narrowband sensors and cannot provide a high resolution image of the investigated scenario.
Through a steady improvement of RADAR based sensing techniques and the continuous increased bandwidth, previously unimagined possibilities open up, both for the accuracy and application area. These techniques combine the high accuracy of optical techniques with longer wavelengths so that airborne particles show a much smaller influence on the measurement. Additionally, the radiation can partially penetrate dielectric material whereby a limited through wall detection and layer thickness estimation is possible.

The applied extinguishing agents in a hazardous scenario have a strong impact on the permittivity estimation due to the high permittivity values of e.g. water. Since the material properties, like the permittivity, are changed by the water content the reflection characteristic of the surfaces is also changed. Hence, the imaging techniques that are widely used on common security robots may be affected by artefacts and in the worst case are show an useless image.

In this paper an ultra-wideband system is used to examine the effect of extinguishing water on the permittivity estimation based on a multilayer reflection concept. Additionally, the permittivity estimation of typical indoor-materials with different water contents will be compared with the analytical results.

**Multilayer Reflection**

The method of summing partial waves is efficient for a single layer, but such calculations becomes awkward for multi-layers. Due to the boundary conditions and the linearity of the Maxwell equations, several transfer matrix methods were developed to calculate the electric field in different layers of an object. Hence, the electromagnetic fields can be calculated for various layer structures, likewise the reflection and transmission coefficients of such complex structures. Therefore, a reflection matrix $I^{(m,m+1)}$ can be associated with each boundary and path matrix $L^m$ can be associated with each layer. $I^{(m,m+1)}$ holds

$$I^{(m,m+1)} = \frac{1}{t^{(m,m+1)}} \begin{bmatrix} 1 & \rho^{(m,m+1)} \\ \rho^{(m,m+1)} & 1 \end{bmatrix}$$

(Eq. 1)

and for $L^m$ it holds

$$L^m = \begin{bmatrix} e^{-iy_m} & 1 \\ 1 & e^{-iy_m} \end{bmatrix}$$

(Eq. 2)

where

$$y_m = \frac{4\pi \cdot f \cdot c_0 \cdot d_m}{\sqrt{\varepsilon_{r,m}}} \sqrt{1 - \left(\frac{\sin \theta_{l,m}}{\sqrt{\varepsilon_{r,m}}}\right)^2}.$$  

(Eq. 3)

c_0 is speed of light in vacuum, $f$ the frequency of the radiated wave and $d_m$ is the thickness of the $m$-th layer ([2]).
For a number of \( M \) layers it can be expressed as
\[
S_{\perp,\parallel} = I^{(01)} \cdot L^{(1)} \cdot I^{(12)} \cdot L^{(2)} \ldots L^{(M)} \cdot I^{(M,M+1)}
\]  
(Eq. 4)

The reflection coefficient and the transmission can be calculated by
\[
r_{\perp,\parallel} = \frac{S_{\perp,\parallel}^{21}}{S_{\perp,\parallel}^{11}}
\]  
(Eq. 5)

and
\[
t_{\perp,\parallel} = \frac{1}{S_{\perp,\parallel}^{11}}.
\]  
(Eq. 6)

Using this relation for the shown single layer and double layer case in Fig. 1 and Fig. 2 the resulting reflection coefficients for the single layer is
\[
r_{\perp,\parallel} = \frac{r_{\perp,\parallel}^{01} + r_{\perp,\parallel}^{12} \cdot \exp(i\gamma_1)}{1 + r_{\perp,\parallel}^{01} \cdot r_{\perp,\parallel}^{12} \cdot \exp(i\gamma_1)}
\]  
(Eq. 7)

and for the double layer
\[
r_{\perp,\parallel} = \frac{(r_{\perp,\parallel}^{01} + r_{\perp,\parallel}^{12} \exp(i\gamma_1)) + (r_{\perp,\parallel}^{01} r_{\perp,\parallel}^{12} + \exp(i\gamma_1)) r_{\perp,\parallel}^{23} \exp(i\gamma_2)}{1 + r_{\perp,\parallel}^{01} r_{\perp,\parallel}^{12} \exp(i\gamma_1) + (r_{\perp,\parallel}^{01} + r_{\perp,\parallel}^{01} \exp(i\gamma_1)) r_{\perp,\parallel}^{23} \exp(i\gamma_1)}.
\]  
(Eq. 8)

Fig. 1. Reflection of the homogenous dielectric material layer 1.

The single layer case as shown Fig. 1 represents the reflection of a wooden plate in air. The reflection at the first boundary between layer 0 and layer 1 is interfered with the reflection coming from the backside of layer 1. The single layer model of a wooden plate is shown in Fig. 1. In Fig. 2 the layer is separated into two layers. The brown layer represents the wood and the blue and brown hatched layer represent the mixture of
water and wood. Depending on the amount of extinguishing water the concentration and the thickness of the layer will increase or decrease. Hence, the permittivity of the layer with water is increased. In [water] it was shown that the water content and the related permittivity change has linear dependency until saturation is achieved.

Fig. 2. A mixture of water and the homogeneous material creates a new layer.

**Hardware Setup**

In recent years, several methods for the generation of ultra-wideband (UWB) signals were introduced. Typically, short pulses in the sub-nanosecond range, or sine waves, which are swept or stepped over a large frequency band are exploited. Due to the high dynamic range and the higher accuracy a network analyzer is used for the signal generation and the coherent detection in the measurement set-up.

The ZVB-20 network analyzer of Rohde & Schwarz is used for the analysis, covering the frequency band from 10 MHz to 20 GHz. Two directive Polytetrafluoroethylene tapered slot-line Vivaldi antennas [3] are mounted in a bi-static configuration where the transmitting and receiving antennas are separated by a distance of 25 cm. The antennas should be linear polarized and the two substrates are connected orthogonal to each other. These antennas can be used in the frequency range from 4.5 to 13.5 GHz.
Simulation Results

Fig. 3 and Fig. 4 illustrate the simulation results of the reflection coefficient for parallel and perpendicular polarization of a wooden plate with a permittivity of $\varepsilon_r = 3$ for different water contents.

The simulation scenario is based on the multilayer model and penetration depth of water is measured with a Vernier caliper as 1 mm. For the calculation of the moisture and the change of permittivity the technique presented in [4] is used. Due to the higher permittivity of the wet material the points of destructive interference that are calculated with equation 4 are shifted to lower frequencies. The high complex part of the permittivity and the resulting loss in the material reduces the reflection at 8 and 17 GHz.

![Reflection Coefficient Plot](image)

Fig. 3. Simulation of the reflection coefficient $r_\perp$ for different water contents for a multilayer model.
Fig. 4. Simulation of the reflection coefficient $r_{\parallel}$ for different water contents for a multilayer model.

**Measurement Results**

Fig. 5 and Fig. 6 illustrate the measurement results of the reflection coefficient for parallel and perpendicular polarization of a wooden plate with a permittivity of $\varepsilon_r = 3$. The MDF board is sprayed with water so that a layer with a moisture is created.

The first measurement shows the reflection coefficients of the wet MDF board and the following measurements show the drying process every 6 minutes. After 18 minutes the plate is dry and the reflection coefficients correspond again to the dry reference measurement. The observed drying process was simulated and is shown in Fig. 3 and Fig. 4.
Conclusion

This paper compares a multilayer reflection model with measurement results performed at a wet surface, with the scope of improving the permittivity estimation in hazardous scenarios. The comparison between
measurements and simulations show good agreement. The developed model for broadband RADAR systems is based on the Abels theory in combination with [4]. The drawbacks of common multilayer characterization techniques, which require a multiple change in the measurement setup by sweeping the angle of incidence or narrow-band analysis of the permittivity are avoided. The introduced techniques open-up new possibilities for the usage on mobile material characterization and localization platforms. In future works the frequency dependency of the permittivity will be examined and the dielectric fingerprint of the materials will be analyzed.

References


