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Characterisation of materials in the millimeter wave frequency region for industrial applications

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Abstract The millimeter wave region up to the lower THz region offers a good penetration ability for many dielectric materials which are in use today. Especially for the quality control of foods within its package, impurities can be clearly identified as long as the package is free from any metallic material. Another field of interest is the quality of welded-, brazed- and soldered joints. The present paper describes the detection and characterization of different materials under test by two different measurement systems. An vector network analyzer and a "Stand Alone MilliMeter wave Imager" called SAMMI developed by Fraunhofer FHR. For the characterization the different materials will be detect with a clustering algorithm in connection with the optimization of the measured data with regard to the problem of ambiguous phase values, called Phase Unwrapping. The permittivity of the different clusters are determined by a reconstruction algorithm.

1 Introduction

Today the non-destructive material analysis plays a major role in several applications, e.g. the quality control of industrial production lines, security applications etc. For those applications a new sensor concept working in the millimeter wave range offers an alternative to present systems, which are based on X-Ray or optical sensors. The advantage is the information about the internal structure of the device under test (DUT), which cannot be collected in the same quality by a system with optical sensors. The frequencies of interest are in the millimeter wave region starting at 30 GHz and ending around 800 GHz. This frequency range offers a better measurement capabilities than IR or optical spectrometers. Due to the shorter wavelengths compared to classical radar applications a better spatial resolution can be obtained. For the calculation of the material parameters we need the physical dimensions of the object and the runtime of the signal inside the device under test (DUT). For multilayer structures a range resolution is necessary, the range resolution can be realized through a pulsed system or the phase measurement with broadband frequency modulated continuous wave (FMCW) or stepped frequency continuous wave (SFCW) system.

The characterization of materials is a critical task for every operational system. For systems in industrial production lines belt systems between 60m/min and 300m/min are typical. A cheap, efficient and fast millimeter wave inspection system could be not realized with a vector network analyzer and a reconstruction for every pixel. Therefore a cheap inspection system called SAMMI was developed to solve these problems in three steps. The first step contains the elimination of ambiguities in the measured phase values, so called Phase Unwrapping, to ensure a precise clustering of the material parameters. In a second step the different materials of the DUT are classified by a cluster algorithm in matters of the measured amplitude and unwrapped phase values. The cluster algorithm allows a graphic presentation of the DUT where the different materials are explicitly distinguishable. In the last step the permittivity of the material is determined for each cluster, i.e. for each material, by a reconstruction algorithm. In this Paper the same steps are performed with a vector network analyzer and compared with the results of SAMMI.

2 Meausurement system

The first very simple measurement system is a mechanical xyz-scanner with a network analyzer (PNA E8361C) from Agilent (Fig. 25.1 on the left) [1]. This system is called materialscanner. The PNA allows the analysis of amplitude and phase information of the DUT with a SFCW mode. With several modules this system allows a frequency range from 10 MHz to 325 GHz. With the three connected linear motors it is possible to scan a three-dimensional area. The second system is called SAMMI

Figure 25.1: On the left is shown the materialscanner with the xvz-motors. SAMMI is shown on the right.

(Fig. 25.1 on the right) and is a continuous wave system at the frequency of 78 GHz.

SAMMI was developed at the Fraunhofer-Institute for High Frequency Physics and Radar Techniques FHR and allows the analysis of amplitude and phase information of the DUT. SAMMI has rotating plates on which dielectric antennas are attached, which sampled a DUT in transmission. An endless belt ensures a continuous flow of material and a DIN A4 sheet is scanned within 20 s. SAMMI has the size of an average laser printer, whereby it is easy to transport. The big advantage of SAMMI is the construction off low cost materials whereby the whole system has a low price in comparison with a vector network analyzer. Due to their low loss at higher frequencies compared to common waveguides two dielectric waveguide tips act as antennas in both systems. Another advantage of dielectric waveguides is their high flexibility, which allows changing simply between the transmission and reflection configuration.

To detect the thickness of the DUT a light-section sensor (C4-1280CS) from Automation Technology are used for both systems.

3 Device under test und measurement method

The measured DUTs are two different plastics which have both the same width and height from 100 mm and differ only in the thickness and the permittivity. The first DUT is PVC (polyvinyl chloride) with a thickness of 7 mm and a permittivity of 3 to 3.5. The second DUT is POM (polyoxymethylene) with a thickness of 4 mm. It is the lower DUT at all amplitude and phase images of this paper. In general has POM a permittivity of 2.9 to 3.8. The two materials were chosen by means of their similar permittivity to show whether they can be distinguished by the clustering algorithm. All samples have a planar structure. To compare the results of both systems the same measurement method is choosen. This means a transmission measurement at a frequency of 78 GHz at SAMMI and a transmission measurement at the frequency range from 75 GHz to 110 GHz at the materialscanner.

4 Simplified signal processing for material characterization

4.1 2D phase unwrapping

In general phase unwrapping describes the elimination of ambiguities in the measured phase values, which are wrapped into the interval $(-\pi,\pi]$, i.e. the phase is known except for multiples of 2π. The two-dimensional phase unwrapping is divided into the path-following and the minimum-norm methods. In opposition to the minimum-norm algorithms, which regard the entire image, the path-following methods consider the image pixel by pixel guided by a certain path. A classical path following method is the quality guided algorithm which is guided by so called quality maps, i.e. matrices whose entries describe the quality of the recorded phase values. As a measure the variance of the phase gradients is used. Another possible measure is the correlation of the phase values [2]. Due to the error rate of the quality guided algorithm for noisy data a modified quality guided method [3] is used here. The modification consists in the valuation of the adjusted phase values after each step and the correction of possible errors to avoid their propagation. The algorithm is subdivided into two main steps, the unwrapping of the recorded phase value and the evaluation of the result by means of a certain quality criterion.

1. The modified unwrapping algorithm starts as the original one at a pixel of high quality in a homogeneous region. For each pixel the adjusted phase is determined by the information of its eight neighbours in a region of 5×5 pixels around the considered phase value, where only those pixels are taken into account which are already unwrapped [3].

2. As criterion for the quality of the adjusted phase value the deviation between the result and an estimate for the unwrapped phase value is established [3]. If the deviation is lower than a certain threshold, the adjusted phase value, calculated in step one, will be hold. Otherwise the determined phase will be discarded and the unwrapping continues at another pixel, i.e. the algorithm starts again at step one.

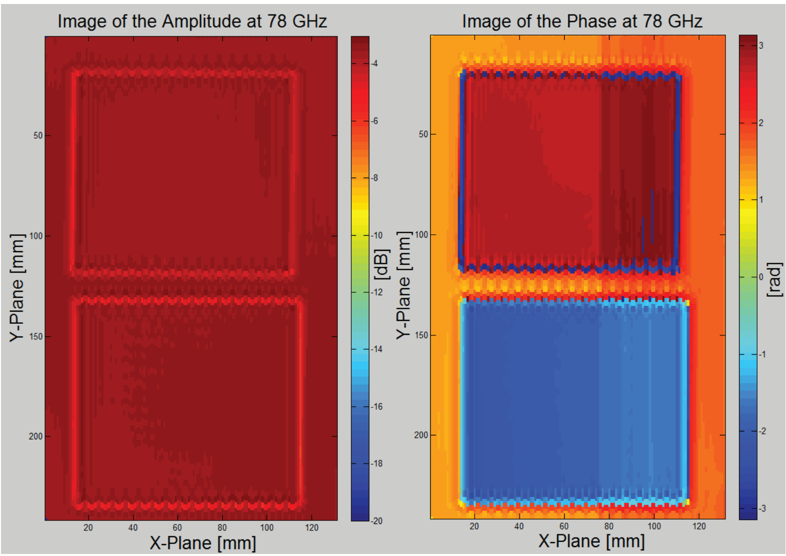

Figure 25.2: Raw data (amplitude and the wrapped phase) from the materialscanner.

Figure 25.2 shows the measured raw amplitude and raw phase from the materialscanner at 78 GHz with the phase values wrapped into the interval $(-\pi,\pi]$. The phase shifts are mainly distinguishable at the upper DUT (PVC) and at the outlines of the DUTs, i.e. there are jumps from $-\pi$ to π between two adjoining pixels. Figure 25.3 shows the unwrapped continuous phase, which is no longer bound to the interval $(-\pi,\pi]$. It is in evidence that the phase jumps within the DUTs have been eliminated. Based on the images of the materialscanner it is visual distinguishable that there are two different DUTs within the image.

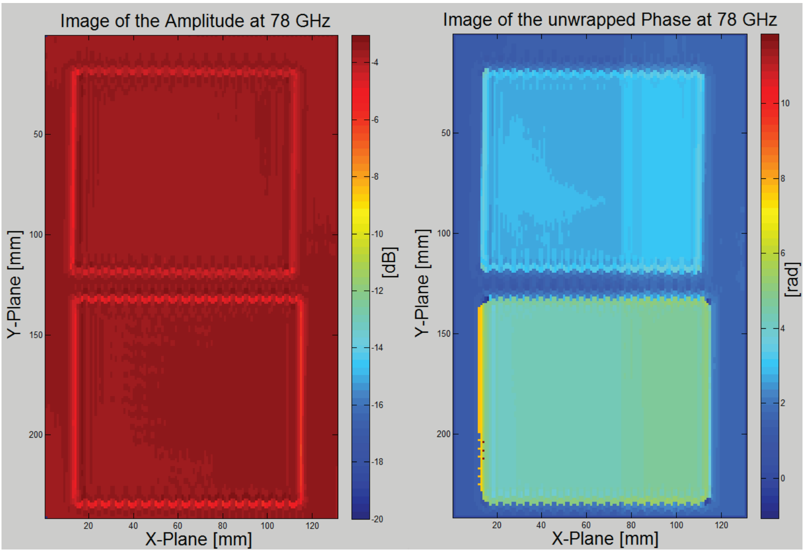

Figure 25.3: Amplitude and the unwrapped phase from the materialscanner.

SAMMI has a pre-processing of the raw data which includes the phase unwrapping. The aim of the pre-processing is a faster data handling for real time application. Figure 25.4 shows the measured amplitude and phase from SAMMI at 78 GHz. This image shows that their are no phase jumps. Based on the images of SAMMI it is visual distinguishable that there are two different DUTs within the image. One current drawback of the preprocessing can be seen at the bottom DUT. A part of the edge of the DUT assumed to the background and hence the DUT it is not rectangular.

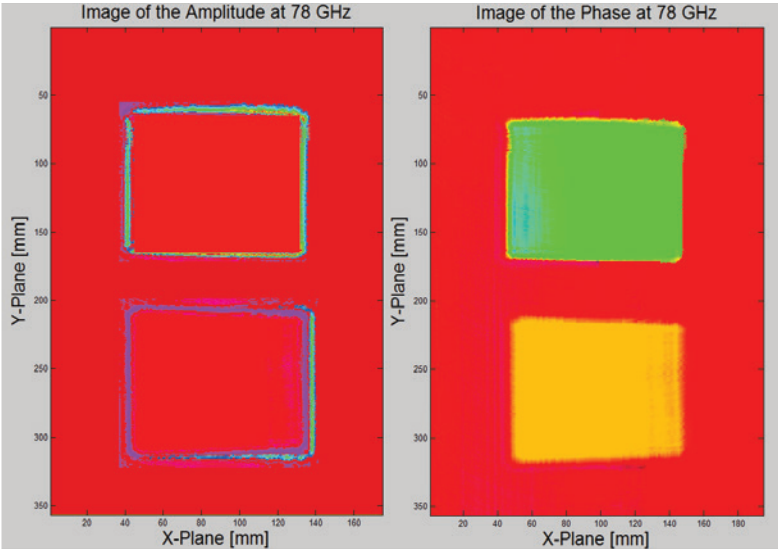

Figure 25.4: Pre-processed raw data (amplitude and the unwrapped phase) from SAMMI.

4.2 Clustering algorithm

The aim of cluster analysis is to identify groups of objects in a certain dataset, which are similar to each other but different from individuals in other groups. However, a cluster algorithm should capture the nature structure of a data set. There are various ways in which clusters can be realized. One of the most straightforward methods is the hierarchical clustering algorithm, which will be described here briefly. Hierarchical clustering can be either agglomerative or divisive.

Agglomerative hierarchical clustering begins with each object of the data-set as an own cluster. Similar clusters are merged after successive steps into subclusters based on chosen linkage functions. The algorithm ends with all objects in one cluster. The divisive clustering method starts with each object in one cluster and ends up with each as an own cluster. However, it is the opposite way of the agglomerative method. Linkage functions are used to determine in which order clusters may merge. E.g. two clusters can be merged to one cluster if its elements are the most similar objects (single linkage) or if their objects are the elements which are most dissimilar (complete linkage). More linkage methods are listed in [4]. The key of this algorithm is the calculation of the so called proximity matrix between two clusters [5]. As basis for the clustering algorithm the unwrapped phase and the amplitude of the objects is regarded (Figs. 25.3 and 25.4).

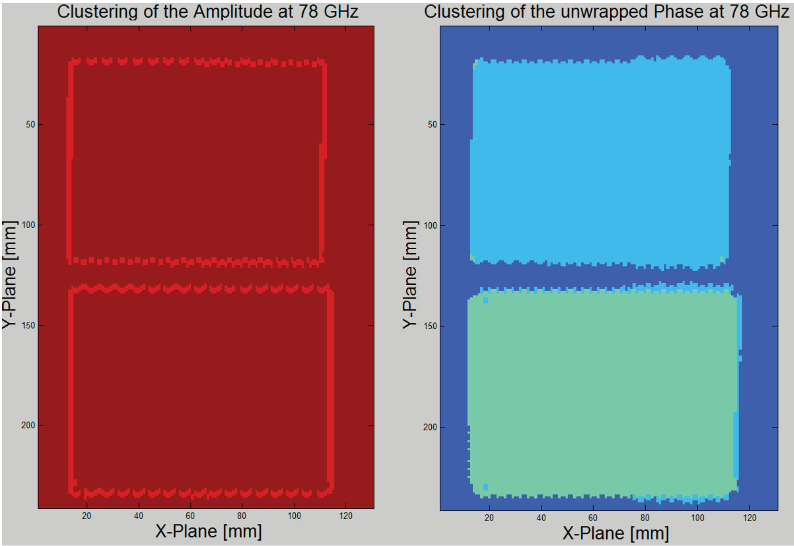

Figure 25.5: Result of the cluster process for the images of the material scanner.

Using the agglomerative clustering algorithm, the result of the cluster process for the images of the material scanner is illustrated in Fig. 25.5. The result for the images of SAMMI is illustrated in Fig. 25.6. For merging the clusters, Ward's method [6] was used. This method uses an analysis of variance approach to evaluate the distances between clusters. Ward's algorithm attempts to minimize the sum of squares of any two clusters that can be formed at each step. The aim is to create clusters of similar sizes. To determine the number of groups in the current dataset, Mojena's stopping rule was applied [7]. The number of clusters is 3.

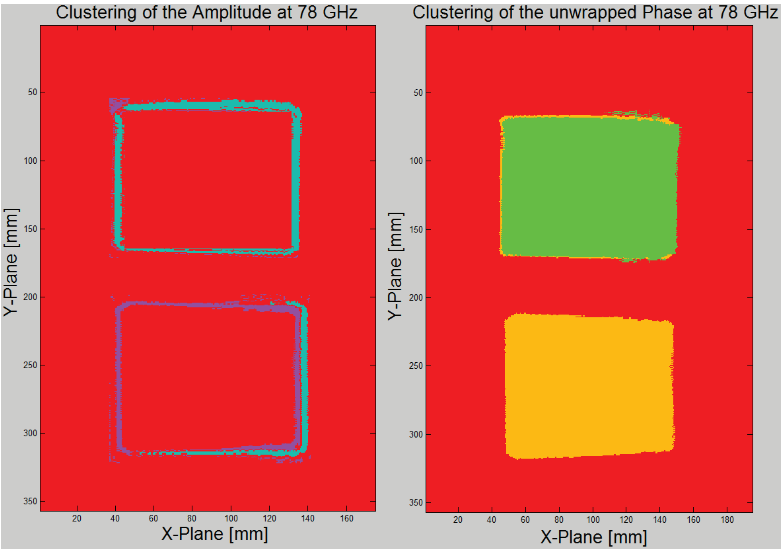

Figure 25.6: Result of the cluster process for the images of the SAMMI.

Comparing the clustered image of the amplitude and of the unwrapped phase, it can be seen, that on the amplitude image only the outlines of the DUTs are detected by the materialscanner and SAMMI. The differences in the amplitude are too similar. For this reason the results are regarded not further. In the clustered images of the unwrapped phase of the materialscanner and of SAMMI are mainly three clusters, i.e. the background, the PVC and the POM sample are clearly reproduced in spite of their similar permittivity.

4.3 Reconstruction of the permittivity

The permittivity is calculated from the time difference between a test section with and without a sample. The time difference is caused by the permittivity of the material which slows down the electromagnetic wave inside the material. This difference is expressed in the frequency domain by a phase difference which can be measured. If the phase difference and the thickness of the material is known, the permittivity can be calculated by using the equation 25.1.

$$\varepsilon_r = \left(\left(\frac{\Delta\varphi \, c_0}{\omega \, d_{DUT}} \right) + 1 \right)^2 \tag{25.1}$$

The cluster algorithm shows that there are only three different materials in the clustered phase image, therefore only the material characteristics of one measuring point of each material need to be reconstructed. For this reason only one pixel in the middle of each material is enough. For the background the reconstruction is not needed because it is not a DUT. The light-section sensor detects a thickness of 3.95 mm for the POM and a thickness of 6.98 mm for the PVC. With the phase value and the measured thickness of the pixel the permittivity of the two different materials can be determined with the equation 25.1.

With the materialscanner will be calculate two different permittivity per DUT. A permittivity at the frequency at 78 GHz and a mean permittivity in the frequency range of 75 GHz up to 110 GHz. The result of the mean permittivity is for PVC 2.92 and for POM 2.84. At a frequency of 78 GHz the permittivity of PVC is 2.92 and of POM 2.83. SAMMI reconstructed a permittivity of 2.94 for PVC and a permittivity of 2.88 for POM. The reconstructed permittivity of SAMMI and the materialscanner are similar and corresponds almost exactly with the theoretical permittivity of the both DUTs.

5 Conclusion

In conclusion a compared between a vector network analyzer and SAMMI for a procedure of non-destructive detection and characterisation of materials was presented. It was shown that SAMMI is a cheap, efficient and fast millimeter wave inspection system which delivers nearly the same quality as a expensive vector network analyzer. Different materials can be distinguished by SAMMI by an clustering algorithm, based on the phase information of a transmission measurement. Previously the phase ambiguities were eliminated by a phase unwrapping algorithm. It was shown that the clustering algorithm detected all samples in each case as one cluster. Based on the classification of the clustering algorithm the permittivity of the different clusters were reconstructed by a reconstruction algorithm. The reconstruction results showed that the permittivity nearly match with the theoretical values.

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