An Evolutionary Algorithm Based Approach to Improve the Limits of Minimum Thickness Measurements of Multilayered Automotive Paints

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We present a novel numerical approach to decrease the limits of the minimum paint thickness measurements of individual layers in multilayered structures using terahertz pulsed technique in reflection geometry. This method combines the benefits of model-based material parameters extraction, a generalized transfer matrix method, and an evolutionary optimization algorithm. The proposed approach has been successfully applied to resolve individual layer thicknesses down to 5 µm in multilayered automotive paint samples.

I. Introduction And Background

Recently, terahertz waves become more and more interesting, especially for inline quality monitoring of thin paint coats during the production process in aircraft and automobile industry. For these applications, the typical layer thickness lies between 10 µm and 50 µm. Therefore, a direct determination of the individual thin layer thicknesses from the time delay Δt between two pulse echoes from front and back surface of the paint layer (Eq. 1) is very difficult.

$$\Delta t = 2nd/c \qquad (1)$$

Where d and n are the thickness and the refractive index of the layer respectively and c is the speed of light in vacuum. The thickness resolution $d_{\min}$ with this model is determined by the pulse length of the terahertz pulse ΔT and can be derived from Eq. 1 as follows:

$$d_{\min} = c\Delta T/2n \qquad (2)$$

Based on Eq. 2, for ΔT = 1 ps and n = 1.5 the thickness resolution is estimated to be about 100 µm. For thinner layers, the pulse echoes, which describe the boundaries of the single layers within the multilayer system, overlap in the time domain so that their time separation cannot be determined precisely. In order to decrease the limit of the minimum measurable thickness, a numerical parameter fitting method to separate overlapping subpulses was proposed [1-2].

In this paper, we present a novel approach, which provides a high robustness even for thin layers with complex search spaces consisting of many local minima.

Firstly, the spectral refractive index and absorption index are extracted. For thin layers, the interaction of the terahertz wave with the sample in low frequency range is minimal. A model-based approach can be used to reduce the uncertainty in this range. The Debye-Model provides a good approximation of the material parameters for a broad band of paint samples.

$$\varepsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau} \qquad (3)$$

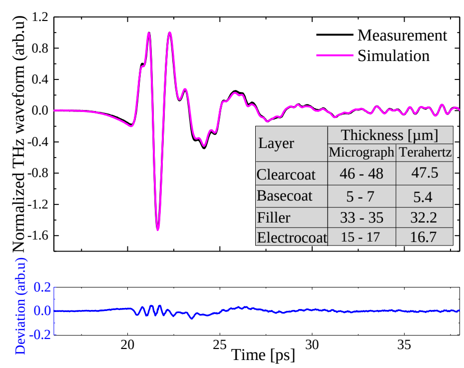
Where, ϵ_s, ϵ_∞ are the static and infinite frequency dielectric constant respectively and τ the dipole relaxation time of the sample.

Secondly, the terahertz pulse is simulated in the time domain with initial values of thicknesses for the entire layers using the already calculated optical material parameters. For the simulation, we utilize the transfer matrix method, which describes the propagation of each subpulse through the material and takes into account the etalon effect, the absorption, and the dispersion of each layer.

Finally, the thicknesses of the individual layers are determined by minimizing the mean square error between the measured and simulated data. In order to increase the probability to find the best solution, even for thin layers with a complex search space, an evolutionary stochastic algorithm instead of the usual deterministic algorithms is used. The real coded genetic algorithm improves with its random population initialization, crossover and mutation the minimum measurable thickness.

II. Results

Our approach was successfully applied to determine the thickness of several multilayer samples, which consist of up to four different layers on metallic and non-metallic substrates. Fig. 1 illustrates an example of the measurement and simulation of four paint layers on a metallic substrate. As can be shown, a good graphical and numerical agreement between experimental and simulated data was obtained. Based on it, the thickness resolution is improved, depending on material parameters, down to 5 µm. With conventional approaches, the minimum thickness is approximately 20 µm.



Layer	Thickness [µm] Micrograph	Thickness [µm] Terahertz
Clearcoat	46 - 48	47.5
Basecoat	5 - 7	5.4
Filler	33 - 35	32.2
Electrocoat	15 - 17	16.7

Fig. 1: THz-TDS measurement in reflection of four paint layers on a metallic substrate.

References

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