Terahertz (THz) Method to Measure Density of a Layer

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Summary

This documents details the concept and practical details of using an Advanced Photonix THz measurement system with an External Reference Structure (ERS) to measure the thickness and density of a foam layer.

Figure 1 – Single Layer Sample Structure

A Time-Domain THz system emits an ultra-short pulse (~0.7 ps) of THz light. When this pulse interacts with a sample, some of the pulse energy reflects back to the sensor and some energy continues to transmit through the sample. The reflected pulses appear like copies of the emitted pulse except they will be delayed as the pulse travels through air (at the speed of light) and through a sample (at a lower speed). Pulse reflections will occur at each interface of the sample, thus a 1 layer sample will generate 2 pulses, while a 2 layer sample will produce 3 pulses. The **TIME** between these reflected pulses is measured and used to determine thickness.

The thickness of a layer is the time delay between the pulses reflected from each surface of the layer (top and bottom) divided by the speed of light for the material in that sample.

The speed of light in a vacuum is 0.29979 mm/ps. This value is very slightly lower when traveling through air, 0.29893 mm/ps. When traveling through a material, the THz pulse travels even more slowly. The ratio of the speed in a vacuum to the speed through the material is known as the Refractive Index (RI) for that material.

Turning this statement around, the Refractive Index (RI) of a material is the ratio of the speed of light through the material to the speed of light through a vacuum. Since we are measuring the length of time that it takes for a pulse to travel through a layer, we can calculate its refractive index by taking the ratio of the time it takes to travel through our sample, Terahertz Time of Flight or (THz ToF) compared to the time it takes light to travel through an equivalent thickness of air or (Thickness ToF).

As an example, if a sample is 1mm thick its Thickness ToF would be:

$$\text{(Thickness ToF)} = 1\text{ mm} \times 2 / c = 1\text{ mm} \times 2 / 0.29979\,\frac{mm}{ps} = 6.671\text{ ps} \qquad [1]$$

to travel through the sample and back to the detector. Since we are measuring in reflection, the pulse that reflects from the far side of the layer has traveled through the layer twice, resulting in the factor of 2 in the formula. If the THz Time of Flight (THz ToF), in passing through our 1mm sample, was measured to be 10.789 ps, then the sample material's RI is calculated as:

$$\text{RI} = \text{(THz ToF)} / \text{(Thickness ToF)} = 10.789\text{ ps} / 6.671\text{ ps} = 1.617 \qquad [2]$$

Notice the RI is always unitless as it is a ratio of two values with the same units, and is always greater than 1.0, since nothing can travel faster than light in vacuum.

The Refractive Index of a solid material is a constant; once measured, knowledge of the RI value allows the direct calculation of the thickness of solid layer materials from the THz ToF. However, this method does not hold true for layers or materials with an unknown RI. Layers with varying material density will have varying RI.

A given thickness of foam consists of a mixture of gas (RI≈1) and material (RI=1.617 in our example). The average RI of the sample, therefore, will have a value between these two limiting values and the quantity (RI – 1) will be proportional to the sample density. The reason it is RI-1 that is proportional to density is that (RI – 1) is a measure of the change in the relative speed of light in passing through the sample to that passing through air, and the density is the relative change in the mass/volume of the material to that of air.

The measurement of THz ToF through the sample can provide a density measurement if it is augmented by an independent measurement of the sample thickness.

In fact, we really don't need the physical thickness, what is needed is the time it would take light to travel through the sample if it were made of air; that is the Thickness ToF value. This time can be used to calculate the refractive index of the foam layer and, as stated previously, the density through calibration to the R-1 value. Sample Thickness ToF values can be determined using the THz sensor and an External Reference Structure (ERS).

An External Reference Structure (ERS), Figure 2, enables measurement of the total sample Thickness ToF without requiring any contact or knowledge of the RI of the sample material, and because the speed of light in air is known, the physical sample thickness can be found.

One common form of an ERS structure consists of a window in front of and a metal reflector behind the sample. In such a configuration, an empty ERS will produce two reflection peaks, one from the inside surface of the window, and one from the metal reflector. With a single layer sample in the ERS, four (4) THz reflection peaks of interest will be observed (as shown in Figure 2b).

The general steps for the calculation of the foam layer Refractive Index are:

1) Measure the time delay between the two surfaces of the empty ERS ($Pk2_E – Pk1_E$). Save this value. [The peak variable (e.g. $Pk2_E$) represents the relative time location of the peak in the sensor data, so the value ($Pk2_E – Pk1_E$) is the time delay between the two peaks.] The result is the empty ERS time delay or (ERS ToF).
2) With a sample in the ERS, measure the time delay of the air spaces above (Pk2 – Pk1) and below (Pk4 – Pk3) the sample.
3) Subtract the delays of the air above and below the sample from the empty ERS time delay measured in Step 1. The result is the (Thickness ToF) of the sample.
4) Measure the time delay between the reflection from the top and bottom of the sample (Pk3 - Pk2). This is the (THz ToF) of the sample.
5) Divide the result of Step 4 by the result of Step 3. This is the foam layer refractive index (RI_F). The quantity (RI_F-1) is proportional to sample density.

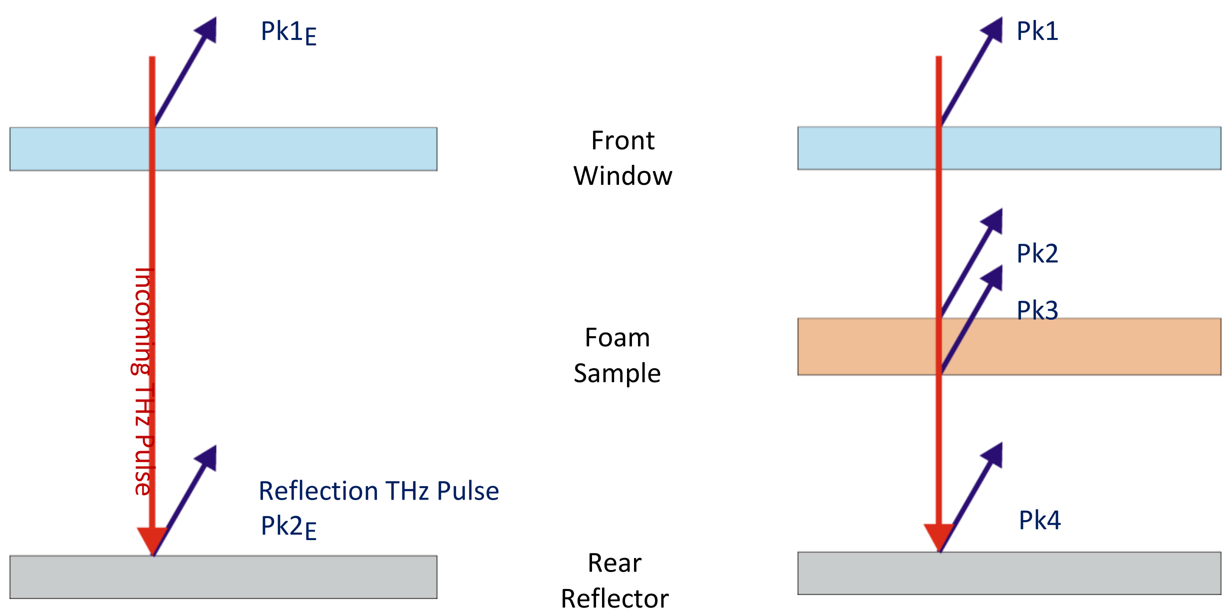

Figure 2 – Sample in External Reference Structure (ERS)

RI_F = (Thickness ToF)/(THz ToF) [3]

In order to determine sample density from the measured RI value, the (RI – 1) value must be calibrated to lab supplied foam density values. For example, if the foam layer density is 9.1 pcf, and we find that the foam RI is 1.4, then the calibration factor for foam of this material is:

CalFactor = (Lab Foam Density) / (RI_F - 1) = 9.1 / 0.4 = 22.75 [4]

This CalFactor can be calculated from laboratory measurements on foam, or from a solid piece of the material component of the foam (e.g., 1.617 from the earlier example). The equation is the same, just using the laboratory measured density of the material and the material RI value.

With the calibration factor, for our next sample of the same foam, the density would be calculated as:

Density = CalFactor x (RI_F-1) = CalFactor x ((THz ToF / Thickness ToF) - 1) [5]

Or

Density = CalFactor x ((Pk3 – Pk2)/((ERS ToF) – (Pk2 – Pk1) – (Pk4 – Pk3)) [6]

This calibration factor will hold for a consistent solid material used to make the foam (e.g., Polypropylene) because the Refractive Index for Polypropylene is a constant. A new calibration factor would have to be determined for a different material (e.g., Polyethylene). Multiple lab standards to demonstrate the linear correlation of the calibration factor are always beneficial.

In the T-Gauge Recipe Client programming language, this equation would be written

DN01 = CalFactor x ((TT03 – TT02)/(ERSps – (TT02 – TT01) – (TT04 – TT03)) [7]