CORRIGENDUM

Corrigendum: Multilayer film thickness measurement using ultrafast terahertz pulsed imaging (2019 J. Phys. Commun. 3 035013)

Dahi Ghareab Abdelsalam Ibrahim1, Safaa K H Khalil2, H H A Sherif3 and M M Eloker1

1 Engineering and Surface Metrology Lab., National Institute of Standards (NIS), Tersa St., El haram, El Giza, Egypt
2 Spectroscopy Department, Physics Division, National Research Center, Giza, Egypt
3 Physics Department, Faculty of Science, Al Azhar University, Egypt

The unit of Layer thickness that appears on the table 2 of section 4 must be replaced by (μm) not (μμm). These corrections and clarifications do not change any of the results and conclusions obtained in the paper.

ORCID iDs

Dahi Ghareab Abdelsalam Ibrahim https://orcid.org/0000-0002-4429-5096
H H A Sherif https://orcid.org/0000-0001-9111-7893
Multilayer film thickness measurement using ultrafast terahertz pulsed imaging

Dahi Ghareb Abdelsalam Ibrahim1, Safaa K H Khalil2, H H A Sherif2 and M M Eloker3
1 Engineering and Surface Metrology Lab., National Institute of Standards (NIS), Tersa St., El haram, El Giza, Egypt
2 Spectroscopy Department, Physics Division, National Research Center, Giza, Egypt
3 Physics Department, Faculty of Science, Al Azhar University, Egypt
E-mail: abdelsalam1975@gmail.com
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Abstract
Terahertz (THz) rays have higher penetration depth compared to visible rays, and hence can be effectively used to measure a geometric thickness of soft samples with no damage. Measurement of such soft samples with contact methods is a challenge in terms of accuracy and speed. In this paper, a terahertz pulsed imaging (TPI) ima3000 system with reflection imaging module has been employed to measure the individual thickness of a multilayer structure made of adhesive soft polymer films with temporal method. Automatic scan of the sample has been carried out and the echoes at each interface are sampled and then detected. The complex refractive index (RI) of the sample has been measured with terahertz pulsed spectra (TPS) 3000 with transmission module. To avoid the incorrect thickness from the measured complex RI due to dispersion, propagation constants of the sample for a given mode and polarization have been extracted by solving the Helmholtz equation, numerically. From the detected delay of echoes and the calculated propagation constants, the geometric thickness of each layer is calculated. Further thickness of an onion leaf as a biological sample was measured based on the propagation constant. Results showed good accuracy with uncertainty budget of 7% of the THz wavelength used.

1. Introduction

Calibration of soft films with an adhesive bonding is intensively used in many applications in engineering and science [1]. Merits of using such soft films are the compatibility with a variety of different materials as well as low processing costs. Moreover, in contrast to welding, no alterations occur at the joint area. In industry, the quality inspection of such soft films is required. Non-destructive testing is preferable for soft films inspection. The utility of using non-destructive testing lies in the protection of the film surface from damage. Moreover, measurement with non-destructive testing methods gives accurate results since it is challenging to control soft samples by destructive testing methods such as a digital micrometer. Due to the limited penetration depth of visible light in thick adhesive films, ultrasonic or x-ray measurements offer insight into the joint characteristics [2]. However, it is found that the contrast mechanisms for both techniques are relatively weak, especially when an adhesive layer (resin) between polymeric components is of interest. The elegant contrast technique at terahertz (THz) rays makes THz time domain spectroscopy (TDS) a perfect approach to the inspection of soft films with adhesive bonds. THz range covers the frequencies (0.1 THz to 10 THz corresponding to wavelengths of 3 mm to 0.03 μm) between microwave and infrared frequencies in the electromagnetic spectrum [3–8]. In 2005, Yasui et al [9] demonstrated tomographic imaging of paint on car body panels using time of flight (TOF)-THz tomography to control paint quality and measure the final paint thickness of both single- and two-layer paints with relatively thick film above 100 μm. Yasuda et al [10] proposed a numerical parameter fitting algorithm to improve the thickness measurement. Recently, Ke Su et al [11] used a simulated model for terahertz propagation in a multi-layered car paint combined with a numerical fitting method to obtain the thickness of each layer. As far as we know, the previous attempts of film thickness measurement were based in calculation on
the measured RI, which may produce incorrect thickness measurement due to dispersion. In this paper, we solved the Helmholtz equation numerically at wavelength 150 \( \mu m \) corresponding to a frequency of 2 THz to extract the propagation constants of the sample being tested at a given mode and polarization. The extracted propagation constants were used instead of the measured RI for calculation of the individual thickness of the multi-layered structure being tested. The complex refractive indices were measured at 2 THz. In this paper, we determine the propagation constants of the sample being tested at a given mode and polarization. The extracted propagation constants of the sample being tested at a given mode and polarization. The extraction of the re
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2. Principle

For each layer of the multilayered structure of figure 1(a), the complex RI of each layer is given by \( \mu_i = n_i + jk_0 \), where \( n \) and \( k \) are the real and imaginary parts (extinction coefficient) of the complex RI, respectively, \( j = \sqrt{-1} \), and \( i = 1, 2, 3, 4 \) is the number of layers as shown in figure 1(b). The first layer is a polyester paper film of thickness \( d_1 \) around 20 \( \mu m \). The second layer is a silicon adhesive film of thickness \( d_2 \) around 90 \( \mu m \). The adhesive resin layer bonds on the polyester paper layer to constitute a cell of thickness \( (d_1 + d_2) \) around 110 \( \mu m \) (as measured by conventional digital micrometer from Mitutoyo, Japan with resolution of 1 \( \mu m \)). The cell is deposited on a small area of a steel substrate then half of the covered steel was further covered by the same cell material to constitute five interfaces; air/polyester, polyester/silicon, silicon/polyester, polyester/silicon, and silicon/substrate, corresponding to numbers 1, 2, 3, 4, and 5 as demonstrated in figure 1(a). The complex RI values of one cell were extracted from TPS spectra to be \( (1.45 + j0.32) \) at 2 THz, and found to be 1.48, since the extinction coefficient is slightly small (lossless sample).

Because the depth resolution depends on the width of the incident THz pulse (around 0.4 Picoseconds (PS) in the used system), so the least measured thickness is around 40 \( \mu m \) at a measured complex RI = 1.48. This means that the thin polyester paper films (20 \( \mu m \)) inside the proposed multilayer structure can’t be resolved by the current system. This makes the used THz system insights only the whole integrated cell (110 \( \mu m \)) as a one layer and the proposed multilayer structure of figure 1(a) turns to only two cells with three interfaces a, b, and c as demonstrated in figure 1(c). In this study, the cell thickness has been investigated individually by the temporal method which based on the time of flight technique. In general, there are two complementary methods to determine the film thickness; temporal method and spectral method. Temporal method is preferable for lower...
resolution, while spectral method is better for high resolution. In the temporal methods, a time delay measurement based on time of flight technique is used to obtain the thickness of a given layer. More clearly, if the wave travels to and from a point, a distance \( d \) away, it takes a time expressed as \( t = 2d/c \), where \( c \) is the speed of light. A pulsed terahertz wave of optical path length \( l \) will produce repetitive pulses of period \( \Delta t = 2l/c \). In the spectral domain, the spectral curve has peaks separated by \( \Delta \nu = c/2l \). If the source of spectral width \( \Delta \nu \) is perfectly mode-locked it forms a pulse of duration \( \Delta t \leq 1/\Delta \nu \). With such a pulse we can just resolve a thickness of \( d = c\Delta t/2\mu \) where 2 factor in the equation corresponds to the round trip of the delay line. For the proposed layers shown in figure 1 (a), the peaks due to reflection from an interface between adjacent layers are well separated when the layer is optically thick. However, for optically thin layers, peaks from their interfaces are not well separated in the time-domain. As seen in figure 1 (c), for pulses propagating at normal incidence, the cell thickness can be calculated directly from the time delay between adjacent reflections which is expressed as \( d_1 = c\Delta \nu \mu_{11} \), and \( d_2 = c\Delta \nu \mu_{12} \), where \( \Delta \nu \) and \( \mu \) are the time separations expressed as optical delay between the reflection pulses. The first reflection peak (a) is due to interface between free space (air, \( n_0 = 1 \)) and the first cell layer. When the complex RI of the first cell, \( \mu_{11} \) is greater than the complex RI of the next cell, a positive peak is observed. The second reflection peak (b) is due to reflection from the boundary between layers of cell1 and cell2. The third reflection peak (c) is due to reflection from the boundary between layers of cell2 and the substrate and is positive when the complex RI of the substrate > \( \mu_{22} \) and vice versa. Sometimes additional peak, positive of negative, may be generated from multiple reflections of the films layers.

2.1. The complex refractive index measurement of lossless and dispersive sample materials

Many polymers are transparent to THz waves. Polymers can be divided into low-loss polymers (\( \mu < 1.55 \)) and high-loss polymers (\( n > 1.60 \)) [12]. In this paper, we used low-loss polymers. In order to determine the individual cell thickness, one needs to know the values of the complex RI of each cell. The complex RI of the polymer cell was measured with the TPS spectra 3000. In the measured THz waveform, the reference signal \( E_{ref}(\omega) \) and sample signal \( E_s(\omega) \) provide the complex-valued optical properties that depend on the angular frequency \( \omega \). For single cell, if \( E_s(\omega) \) and \( E_{ref}(\omega) \) is the Fourier transform of the raw THz waveform measured from a sample and a reference, respectively. The complex RI of the polymer cell can be obtained from the formula of Duvillaret et al [13] as follows:

\[
\frac{E_s(\omega)}{E_{ref}(\omega)} = T e^{-\frac{\alpha(\omega)}{2}} e^{-j2\frac{2\pi}{\lambda}(n(\omega)-1)d} = |R| e^{i\phi},
\]

where \( \alpha(\omega) \) is the absorption coefficient, \( T \) is the fraction of the electric field transmitted through the medium1/medium2 interface and is expressed by the Fresnel equation \( T_{1 \rightarrow 2} = (2n_1/(n_1 + n_2)) \), \( \lambda \) is the wavelength, \( d \) is the thickness of the cell, \( \phi \) is the relative phase, and \( R \) is the reflection coefficient. The frequency-dependent complex index values of refraction, \( n + jk \), are given as follows:

\[
n(\omega) = 1 + \frac{c}{\omega d} \phi,
\]

\[
k(\omega) = -\frac{c}{\omega d} \ln(R/T),
\]

where the absorption coefficient can be calculated from the extinction coefficient as \( \alpha(\omega) = (4\pi/\lambda)k(\omega)/c \). For sample materials with low absorption coefficient, the Fresnel transmission coefficients are real-valued. Due to dispersion, an error arises in the measured complex refractive indices. It is evident \textit{a priori} that this error in refractive index produces an error in the thickness measurement of the cell being tested. To minimize this error, we solved numerically the scalar Helmholtz equation to obtain the propagation constant for each cell as described in section 2.2.

2.2. Numerical calculation of propagation constants and the field profiles for TE modes

We consider a lossless multi-layer guiding configuration [14]. When the multi-layer structure is placed across the path of a travelling planar wave a one-dimensional wave equation in space domain for a linear medium with zero dispersion is given with the scalar Helmholtz equation expressed as follows:

\[
\frac{\partial^2 E_y}{\partial x^2} + k_0^2 n^2(x) E_y = 0
\]

\( E \) is the value of the electric field strength, \( k_0 = 2\pi/\lambda \) is the wave number, \( \lambda \) is free-space wavelength, and \( n \) is the refractive index which in the absence of dispersion is frequency independent. In the presence of dispersion, equation (4) when the propagation in y-direction can be written with the effective index \( n_{eff} \) as:
The results of cell thickness have been compared with those calculated when the thickness of layer $m$ was performed in searching for the propagation constant $\beta$. The propagation matrix which propagates fields across all interfaces is obtained if we propagate the strip waveguides. Here, the propagation constant $\beta$ is replaced with the measured complex RI of 1.48 as shown in figure 1(b). Two propagation constants were obtained at frequency of 2 THz as summarized in table 1.

| Mode   | Propagation constant |
|--------|-----------------------|
| TE(1)  | 1.40                  |
| TE(2)  | 1.15                  |

The exact dispersion relations can be derived using the transfer matrix approach for the multi-layer configuration under investigation as:

$$\gamma^2 - \beta^2 = 0,$$

where $\gamma$ is the propagation constant of the guided mode and $\beta$ is the propagation constant of the guided mode of the slab and is obtained if we propagate fields across all interfaces. Let $\gamma^2 = \beta^2 - n^2 k_0^2$, the solution of the wave equation is

$$E_{fi}(x) = A_i e^{\gamma_i (x-x_{i-1})} + B_i e^{\gamma_i (x-x_{i-1})},$$

The boundary conditions of TE (transverse electric i.e., with p-polarized photons) mode (where the incident electric field is parallel to the interfaces of the layers) at the interfaces of layers are given as follows:

$$E_i(x)|_{x=x_{i-1}} = E_{i-1}(x)|_{x=x_{i-1}}$$

The above equation (12) determines the electric fields at an arbitrary location within layer $i$ once the values of fields are known at point $x_i$. Here, this formalism was applied to analyze the proposed structure. The test was performed in searching for the propagation constant $\beta$ and then determining the profile of the electric field. The algorithm was applied to only one polymer cell with thickness of 110 $\mu$m and complex RI of 1.48 as shown in figure 1(b). Two propagation constants were obtained at frequency of 2 THz ($\lambda = 150$ $\mu$m) as summarized in table 1.

Field profiles of TE(1) and TE(2) modes corresponding to the obtained two propagation constants are shown in figure 2. The fields obtained by this method are used to get information about the scattering attitude of the strip waveguides.

Here, the propagation constant ($n_{eff}$) at the first mode TE(1) can be applied in equation (13) to calculate the cell thickness $d$, where $\Delta t$ is the time delay of the reflected THz pulse measured experimentally from the TPI as follows

$$d = (c\Delta t)/(2n_{eff}).$$

The results of cell thickness have been compared with those calculated when $n_{eff}$ is replaced with the measured complex RI (with TPS spectra).
3. Experimental setup

The schematic diagram of the terahertz pulsed imaging (TPI) ima 3000 system \([15]\) from Teraview is shown in figure 3(a). This system offers a frequency range of 0.06–3 THz corresponding to a wavelength range of 5–0.1 mm with a maximum dynamic range around 75 dB. The setup is built with GaAs photoconductive antennas (PC-antennas), namely, emitter and receiver. An 80-femtosecond (fs) titanium: sapphire (Ti:Sa) laser operating at a fundamental wavelength of 800 nm and with a repetition rate of 76 MHz is divided into two paths and commences into separate optical fibers linked to the TPI core system and the separate plate scanning unit. After leaving the output from the optical fibers in the plate scanning unit, the pump and probe beams are used to illuminate the terahertz emitter and receiver, respectively. The emitter and receiver are contained in a compact cartridge unit with lenses to focus the laser beams onto the gaps of the photoconductive emitter and receiver antennae. A delay line is incorporated into the probe beam to change the difference in optical delay between the incoming terahertz pulse and the probe laser pulse at the receiver. A bias is applied across the emitter and the receiver to generate a time gated output signal.

Both the delay position and the amplified receiver signal are then digitized and interpolated to obtain the terahertz electric field as a function of optical delay at discrete time distances. The terahertz output from the emitter is focused by a silicon lens at the front of the terahertz probe to a diffraction-limited spot on the sample being analyzed. The terahertz reflection by the sample is collected by the same lens and focused onto the receiver as shown in figure 3(a). The terahertz pulse is reflected first off the outer surface and then at later times from any subsurface structures within the multi-layered structure resulting in multiple pulses returning to the receiver. By
moving the sample across the fixed terahertz focus, THz waveform is taken at many points mapped over the surface of a sample resulting in a three-dimensional (3D) image map as a function of time delay.

4. Experimental results and interpretation

Figure 3(b) shows the C-scan image scanned over the black rectangular area of a 10 mm by 19.8 mm area of the multi-layered structure demonstrated in figure 1(c). The image is discretely sampled over 512 data points and acquired in less than 50 min. By analyzing the temporal structure of the THz waveforms returned from the layers in reflection geometry, the return time of reflected pulses directly correlates with the location of the layers interfaces along the propagation direction of the beam. In more detail, the material information at the internal interface could be estimated from the output signal. When a THz pulse is applied to a multi-layered structure having interfaces a, b, c as demonstrated in figure 1(c), the reflection pulses from each interface, appear as a sequence of pulses. The amplitude and the phase are determined by the complex refractive index of the layers at each interface. As seen in the 3D top view of figure 3(b), only 3 sets numbered from left to right as a, b, and c are obtained. The sets are corresponding to the reflections from: double cells, single cell, and substrate, respectively.

Time domain profiles of one point on the surface of the sets c, b, and a are shown in figures 4(a), 4(c), and 4(e), respectively. A THz pulse incident on the multi-layered structure penetrates through different adhesive layers. At each interface or abrupt change in refractive index, a portion of the THz pulse is reflected back to the detector. By measuring the arrival time of these surface and interface reflections, polymer cell thickness can be determined. Spectroscopic information can be extracted by applying the fast Fourier transformation (FFT) on the reflected pulses. The Fourier transformed spectra of figures 4(a), (c), and (e) are shown in figures 4(b), (d), and (f), respectively. As can be seen in the Fourier transform spectra, many resonant peaks (see blue curves in figures 4(d) and (f)) were found. The blue curves are the peak analysis and called ‘peak fitting’ which means constructing a peak model or mathematical function that has the best fit for our data points. The peak fitting is used to show each curvature (or shoulder) in terahertz frequency domain waveform as a separate peak [16].

The detected resonant frequency peaks of figures 4(d) and (f) against the location of the layers interfaces along the propagation direction of the beam are summarized in table 2 and the plotted data are shown in figure 5(a).

As seen in figure 5(a), the resonant frequency peaks are decreasing with increasing the film thickness. Also, the linear fitting shows that the locations of the resonant frequencies are fluctuated in the region between layer thickness of 110 μm and 150 μm, which is expected to be an air gap between the two polymer cells.
The importance of showing the Fourier-transformed spectra is to detect the resonant frequency peaks corresponding to the location of layer thickness. It is worth noting that when the layer film is thin, the spectrum showed no resonance but similar features to the reference spectrum. Based on this fact, it could be said that the peaks 1, 2, 3 appeared in the temporal waveform of figure 4(e) are reliable, while peaks 4 and 5 are fake due to multi-reflections inside polymer cell1 and polymer cell2 as shown in figure 6(a). The change of complex RI at interfaces a, b, c of the sample (double polymer cells) produces three peaks in the terahertz waveforms as shown in echoes present pulses 1, 2, and 3 in figure 6(a1). The higher peak pulse 4 corresponds to multiple reflections of polymer cell1, while pulse 5 corresponds to multiple reflection of polymer cell2 [17, 18]. As seen in Figure 6(b1), the peak 3 provided a large reflected signal because the greater complex RI (greater than 2.5) resulted in a higher reflection coefficient from the steel substrate. The complex RI of one polymer cell of the sample (see figure 6(a2)) was measured using TeraView’s TPS spectra 3000. Schematic diagram of the TPS spectra 3000 is shown in figure 5(b). To calculate the real and imaginary parts of the complex RI of the polymer cell, a background or instrument terahertz response waveform is first acquired. When the polymer cell sample is placed into the sample compartment, a terahertz response waveform is obtained. The signal height is reduced due to terahertz absorption by the sample and the peak position is shifted due to the complex RI of the polymer paper and resin materials of the cell. Applying a fast Fourier transform (FFT) to the terahertz electric field waveforms, frequency responses are produced. By using equations (1)–(3) and one experimental value of the transfer function, it is possible to extract the complex RI that is expressed as a function of the real RI (n) and the extinction coefficient (k) that describes the strength of the relative absorption loss at a particular frequency.

The complex transfer function stands for the ratio of $E_r(\omega)/E_{ref}(\omega)$ given in equation (1). From the obtained frequency responses of the sample and the reference, the absorption coefficient spectrum $\alpha(\omega)$, and the frequency dependent terahertz real RI, $n(\omega)$, and imaginary RI $k(\omega)$ spectra are extrapolated to other frequencies. Prior works of Rutz et al [19], demonstrated that the index of refraction is constant throughout the THz range of 0.2 to 2.5 THz. Figures 6(b1) and (b2) show the extracted real RI and absorption coefficient spectra of one polymer cell of the sample. In this study, the real and imaginary parts of the complex RI of the polymer cell was measured at a frequency of 2 THz which corresponds to a wavelength of $\lambda = 150 \mu m$. The real part was

| Layer thickness (\(\mu m\)) | 0  | 110 | 130 | 220 |
|-----------------------------|----|-----|-----|-----|
| Resonant frequency (THz)    | 1.4| 0.9 | 0.8 | 0.45 |

Figure 5. (a) Resonance frequencies versus the thickness of the layer film, experimental data: solid line with squares, linear fitting: dotted line. (b) Schematic diagram of the TPS spectra 3000 in the transmission module from Teraview. BS, beam splitter; M, mirror.

Table 2. Layer thickness against detected resonant frequencies of figures 4(d) and (f).
The thickness of each polymer cell via equation calculated to be 1.45, while the imaginary part was found to be 0.32. By taking the square root of the sum squares the measured RI was found to be 1.01.

The presence of air gaps between the double polymer cells. Since the calculation has been done for only one cell, the thickness of cell2 seems bigger than cell1 since we attribute that to the expected air gap.

The thickness Cell1 with the average $\Delta t_{ba} = 0.9943 \text{ ps}$ and the measured RI $1.48$ is calculated as $d_{eff} = (0.0003 \text{ (ps) } \times 0.9943 \text{ (ps)})/(2 \times 1.40) \cong 107 \text{ m}$, while with the measured RI was found to be 101 $\mu m$. Cells thickness calculated based on $n_{eff}$ and the measured RI are summarized in table 3. As seen in table 3, the thickness of cell2 seems bigger than cell1 since we attribute that to the presence of air film gap between the double polymer cells. Since the calculation has been done for only one depth profile of figure 4(e), we anticipate the thickness measurement is varied with different profiles. Therefore, we calculated the thicknesses of cell1 and cell2 from ten profiles at different locations on the surface of set (a) of figure 3(b). The ten profiles of the temporal THz wave forms are represented as 2D (z-y) B-scan image, where z stands for the optical delay. There are some variations among the ten profiles. These variations have been taken in calculation of the uncertainty in measurement.

The thickness of the Cell1 with the average $\Delta t_{ba} = 0.9943 \text{ ps}$ and effective RI $1.40$ is calculated as $d_{eff} = (0.0003 \text{ (ps) } \times 0.9943 \text{ (ps)})/(2 \times 1.40) \cong 107 \text{ m}$. The thickness Cell1 with the average $\Delta t_{ba} = 0.9943 \text{ ps}$ and measured RI $1.48$ is calculated as $d_{meas} = (0.0003 \text{ (ps) } \times 0.9943 \text{ (ps)})/(2 \times 1.48) \cong 101 \text{ m}$. The thickness Cell2 with the average $\Delta t_{cb} = 1.2023 \text{ ps}$ and measured RI $1.48$ is calculated as $d_{meas} = (0.0003 \text{ (ps) } \times 1.2023 \text{ (ps)})/(2 \times 1.48) \cong 122 \text{ m}$. As seen in table 3, the obtained thickness of cell2 is bigger a bit as compared with cell1 due to the expected air gap as demonstrated in figure 5(a). The uncertainty in measurement due to repeatability was calculated to be 5 $\mu m$ for Cell1 and 13 $\mu m$ for Cell2. Uncertainty budget due to many sources is explained in section 5. To confirm the validity of the proposed numerical method, we tested a biological thickness of an onion leaf of around 72 $\mu m$ (as measured by conventional digital micrometer from Mitutoyo, Japan with resolution of 1 $\mu m$) with the same previous methods (TPI imaga 3000 to extract the time delay difference $\Delta t$ and TPS spectra 3000 to extract the measured complex refractive index). The measured complex RI, the complex effective RI, and the time delay

**Table 3.** Calculation the thickness of the polymer cell with measured RI (measured with TPS spectra 3000 in the transmission module from Teraview) and effective RI (calculated numerically with Helmholtz equation).

| Time delay diff. (ps) | Cell thickness (μm) |
|-----------------------|---------------------|
| $\Delta t_{ba} = 0.9943$ | Measured RI (1.48) Effective RI (1.40) |
|                       | 101 107            |
| $\Delta t_{cb} = 1.2023$ | Measured RI (1.48) Effective RI (1.45) |
|                       | 122 124            |

*Figure 6.* (a1) Scheme of the time-domain pulses after propagation in the sample, dashed lines due to the reflection at interfaces a, b, c through the sample, while the solid lines at numbers 4, 5 correspond to multi reflections inside cell1 and cell2, (a2) photograph of one cell. (b1) Extraction of the real RI, (b2) Extraction of absorption coefficient of one polymer cell of the sample measured using TPS spectra in the transmission module.
difference of the onion leaf sample are listed in Table 4. The measured complex RI of the onion leaf was found to be 1.05, while the $n_{ef}$ calculated numerically with the Helmholtz equation was found to be 1.00. The time delay difference $\Delta t$ measured with TPI imaga 3000 was found to be 0.49 ps. The thickness of the onion leaf with $\Delta t = 0.49$ ps and effective RI $= 1.00$ is calculated as $d_{eff} = (0.0003 \text{ (ps)} \times 0.49 \text{ (ps)})/(2 \times 1.00) \cong 73 \mu m$. While the same onion leaf with $\Delta t = 0.49$ ps and measured RI $= 1.05$ is calculated as $d_{meas} = (0.0003 \text{ (ps)} \times 0.49 \text{ (ps)})/(2 \times 1.05) \cong 70 \mu m$. The extracted effective refractive indices in Tables 3 and 4 for the tested multilayers sample and the onion leaf sample show the significance of using the proposed numerical method in film thickness measurement. We claim that the calculated thicknesses by the proposed numerical method approach the nominal values, which confirms the calculation with zero dispersion.

### 5. Uncertainty in measurement

The uncertainty budget was calculated from different sources. The first source is due to repeatability in measurement. Here, we used the average of 10 measurements for the calculation of the geometric thickness. Therefore, the uncertainty $u_i$ associated with this source is calculated to be $u_i = s/\sqrt{10} = 5 \mu m$, where $s$ is the standard deviation. The second source of uncertainty $u_2$ was attributed to the deviation of the raw data which are commonly affected by a multitude of system-inherent or environmental side effects, frequency-dependent antenna response, parasitic interferences, water vapor absorption lines, etc. Lagarias et al [20], used an algorithm based on minimizing the difference between the measured and the theoretical transfer function to minimize the error in thickness measurement. The uncertainty based on [19] is in the range of 2 $\mu m$. The third uncertainty in measurement $u_3$ may be caused by the variation of the RI throughout the THz range (0.2 to 2.5 THz) since it is not exactly constant as demonstrated in [19]. Also, the finite-difference approximation of discrete solution of Helmholtz equation produces an error in effective index calculation and hence varies both the thickness and frequency. The uncertainty in RI measurement $u_4$ was calculated to be $\pm 0.02$ corresponds to a thickness of 3 $\mu m$. The fourth source of uncertainty $u_4$ may be caused by the non-normal incidence of the THz rays on the sample. The deviation from orthogonality is most likely $\theta = 2^\circ$. This gives uncertainty $u_5$ calculated from $d = (c\Delta t)/(2\mu)c\cos(\theta)$ to be 0.15 $\mu m$. The fifth source of uncertainty may be caused by the position error of the sample and the reference. It is worth noting that THz-TDS measurement requires a separate measurement on a reference mirror. In practice, it is difficult to place the reference mirror accurately at the same position of the sample. Whereas a small difference $\Delta z$ between the sample and reference position is not problematic for transmission THz-TDS, while for reflection THz-TDS, a phase-shift is introduced in the frequency-dependent reflection coefficient $R = R(\omega)\exp(i\omega2\Delta x)$. This leads to an additional slope on the phase difference $[21]$ produces an uncertainty in measurement $u_6$ in the range of 1 $\mu m$. If the sources of the uncertainty components are independent, the combined standard uncertainty $u_c$ is calculated by $u_c = \sqrt{\sum u_i^2}$. Thus, the combined standard uncertainties of the thickness measurement were estimated to be 5.5 $\mu m$. The expanded uncertainties of the measurement results are calculated as $U = q.u_c$, where $q$ is the coverage factor. For $q = 2$, $U = 11 \mu m$, which is a 7% of the THz wavelength used.

### 6. Conclusion

In summary, we have measured the individual thickness of adhesive layers on multilayered adhesive structure comprised of thick and thin polymer films with the TPI system. Due to dispersion, the complex measured RI may vary slightly and hence an error in thickness measurement may arise. Numerical calculation has been performed to minimize this error via solving Helmholtz equation to obtain the propagation constant or the effective refractive index. Sources of uncertainty were considered, and the uncertainty budget was estimated to be 7% of the THz wavelength used. The terahertz results were compared with the results measured with a digital micrometer and the results were in a good agreement. THz-TDS opens the door for a wide range of non-destructive and contact-free testing procedures for adhesive layer measurement. Merits of using the TPI are: non-contact measurement, fit for a variety of adhesive films, able to measure the thickness of individual layers in
multilayered structure with reasonable accuracy; and able to provide maps of thickness distribution over a surface compared to single point measurements. Furthermore, it can measure the paint thickness and monitoring wet to dry transformation processes. Since the depth resolution of the TPI system is 40 μm corresponding to THz pulse width of 0.4 THz, the thinnest layer of 20 μm in the multilayered structure can’t be resolved. To resolve this thinnest layer, a THz pulse width of 0.1 THz is required and this will be our research study in the near future.

ORCID iDs

Dahi Ghareab Abdelsalam Ibrahim @ https://orcid.org/0000-0002-4429-5096
H H A Sherif @ https://orcid.org/0000-0001-9111-7893

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