Measurements of Leaf Water Content Using Terahertz Radiation

Sillas Hadjiloucas, Member, IEEE, Lucas S. Karatzas, Member, IEEE, and John W. Bowen

Abstract—A novel technique for the noninvasive continuous measurement of leaf water content is presented. The technique is based on transmission measurements of terahertz radiation with a null-balance quasi-optical transmissometer operating at 94 GHz. A model for the propagation of terahertz radiation through leaves is presented. This, in conjunction with leaf thickness information determined separately, may be used to quantitatively relate transmittance measurements to leaf water content. Measurements using a dispersive Fourier transform spectrometer in the range of 100 GHz–500 GHz using Phormium tenax and Fatsia japonica leaves are also reported.

Index Terms—Dispersive Fourier transform spectrometer, leaf water content, null-balance transmissometer, pseudocoherence, terahertz.

I. INTRODUCTION

The quantitative determination of water content in leaf tissues is of great concern to most physicochemical and environmental plant physiologists, as well as plant breeders, biotechnologists, and genetic engineers. When plant cells are not more or less saturated with water, they cease to function normally and the plant is said to be subject to water stress. This results in, at best, reversible growth inhibition, and can lead to irreversible cell damage.

For water potential investigations at the cellular level, the pressure probe technique (which can only be applied under strict laboratory conditions) is widely used [1]. This technique, however, cannot always provide accurate results at the tissue level, as averaging of the measurements over a large area requires the assumption that the cells behave collectively as a perfect osmometer, an assumption that is not valid under nonsteady nonisothermal conditions. At the tissue level, most present techniques concentrate in measuring either the energy status of water or the water content of plants. These techniques, however, are either destructive (e.g., pressure chambers [2] or the balancing pressure technique [3]) or preclude continuous observation of water uptake, evaporation, and transpiration under nonsteady-state conditions (psychrometers [4]). Indirect observation of these parameters is usually performed using porometers [5] that measure the hydraulic resistance or conductance at the leaf surface (usually ignoring boundary layer effects). Alternatively, leaf thickness measurements using leaf clamps and linear variable differential transformers (LVDT’s) (which may introduce errors due to pressure applied to the leaf in the course of the measurement) [6] have also been used, but only provide indirect measurements of changes in relative water content and leaf water potential. More recently, the employment of optical techniques and, in particular, of optical fibers [7] in measuring leaf thickness using a reflectance-type-amplitude modulated displacement transducer have shown considerable advantages over conventional LVDT’s, in that they do not introduce errors by applying pressure to the leaf during the measurement and do not require compensation for the leaf temperature. Furthermore, the optimization of the emitting and receiving angles of the fibers (a technique that has been developed in our laboratory) [8] has shown two orders of magnitude improvement in responsivity and improved resolution over conventional optical techniques. However, errors can still arise in the determination of leaf water content from measurements of leaf thickness alone.

In this paper, an alternative technique for measuring leaf water content based on terahertz transmissometry is investigated. It is well known that terahertz-frequency (i.e., millimeter and submillimeter wave) electromagnetic radiation is strongly absorbed by water. The measured transmission of a leaf depends on the total absorption, which depends on the optical path length of water through which the beam is transmitted, which, in turn, depends on the water content. When a plant is subject to water stress, the path length of water through which the beam is transmitted is reduced, while that of the other plant materials is unaffected. Therefore, a transmission measurement can be directly related to water content.

The technique offers a number of advantages as follows:

1) the method is nondestructive and noncontact;
2) minor angular misalignments between the leaf surface and the incident beam have a fairly limited effect;
3) the terahertz beam can have a cross section which averages over a large section in the leaf structure.

Due to the wavelengths involved, leaf surface irregularities do not affect the measurements through induction of excessive scattering. Furthermore, transmission measurements at microwave frequencies are impractical because the diffraction-limited minimum spot size for a free-space beam is too large to avoid beam spillover around most leaves, while in the infrared and optical parts of the spectrum, strong chlorophyll...
absorption masks that due to water. The terahertz frequency band is, therefore, a unique window in which this type of measurement may be made.

In the following section, a null-balance transmissometer and a single-pass dispersive Fourier transform spectrometer (DFTS) are described. Measurements demonstrating the relationship between leaf water content and transmission are presented using the null-transmissometer for spot-frequency, and DFTS for broad-band operation (100 GHz–0.5 THz). The proposed technique is suitable for noninvasive continuous monitoring of water uptake and translocation from individual leaves and complements the independent work of Mittleman et al. [10] who used a transmission imaging setup consisting of a femtosecond Ti:sapphire laser, a scanning optical delay line, and a gating technique to obtain images of leaves at different stages of drought.

Both instruments used in this paper are based on a hybrid Mach–Zehnder/Martin–Puplett interferometer and use high-density polyethylene lenses to control the diffractively spreading beams [11]. While their overall size and number and location of lenses differ, the layout of beam-splitting and beam-combining components is similar, and the principle of their operation may be described with reference to Fig. 1.

A. Null-Balance Transmissometer

Spot-frequency measurements of leaf transmittance were carried out using the null-balance transmissometer shown in Fig. 1. A corrugated feed horn launches the beam from a 94-GHz IMPATT oscillator (10 mW) through a wire grid $A$ to ensure polarization purity. A grid $B$ with wires at 45° splits the beam into two orthogonal linearly polarized components. Each takes a different path: one being transmitted through the sample, while the second, the reference beam, travels through an adjustable grid and reflector arrangement. The beams are recombined at a second 45° grid $C$, the resultant traveling to an analyzer grid $D$ and detector.

The adjustable grid $E$ may be rotated about its optic axis to change the amplitude of the reference beam; this depending on the angle between the grid wires and incident polarization. Moving the roof mirror $F$ modifies the path length of the reference beam. If the amplitude and phase of the reference beam are exactly matched to those of the beam transmitted through the sample, the resultant beam, on recombination, will have the same (linear) polarization as the input beam prior to splitting. The analyzer grid $D$ is oriented to reflect all of this polarization and, in this balanced state, a null is recorded at the detector. If the amplitude and phase of the two beams are not matched, the recombined beam will have a component which will be transmitted through the analyzer grid to the detector, registering an imbalance. Jones matrices (see Appendix) may be used to relate the angle between the orientations of the reference-beam grid $E$ that result in nulls to the amplitude transmission coefficient of the sample $|\tilde{\mathcal{A}}|$.

$$|\tilde{\mathcal{A}}| = \cos^2 \gamma$$

where $\gamma$ is half the angle between adjacent null orientations measured about the reference-beam grid orientation that transmits all of the incident polarization.

The use of a null-balancing technique means that the measurement precision depends on the precision with which the null angles can be measured and is independent of source
and detector fluctuations (which affect both the sample and reference beams in equal proportion).

The IMPATT oscillator was square-wave modulated at 1.5 kHz and the output from the detector, a Flann Microwave point-contact crystal detector fitted with a corrugated feed horn was fed into a lock-in amplifier. The lenses are 42 mm in diameter and the instrument is mounted on a baseplate which is 500 mm \( \times \) 380 mm. The beam at the sample location has a Gaussian transverse amplitude distribution with a 1/\(e\) amplitude half-width of 10 mm.

B. DFTS

Wide-band measurements of leaf transmittance were carried out using a DFTS. The system layout is similar to that in Fig. 1 with the exception of the omission of the rotatable reference grid \( E \) and a different arrangement of lenses. The IMPATT oscillator is replaced by a wide-band high-pressure mercury arc lamp source and the detector is a cyclotron resonance enhanced InSb hot electron bolometer.

As in the transmissometer, the beam is split into two orthogonal linearly polarized components by a wire grid beam splitter \( B \). One of these travels via the movable roof mirror \( F \) before it is recombined with the other at the second grid \( C \), the resultant propagating through an analyzer grid \( D \) to the detector. If the roof mirror \( F \) is moved back and forth, the degree of ellipticity of the polarization of the recombined beam changes due to the changing phase relationship between the two partial beams. The analyzer grid \( D \) selects one plane of polarization and, if the mirror is driven in one direction through the zero path difference position, the detector records an interferogram that is the squared modulus of the autocorrelation function of the time-dependent field of the input beam. Fourier transformation of the interferogram gives the power spectrum of the source. Placement of a sample in one of the partial beams modifies the interferogram. The ratio of the complex Fourier transforms with and without the sample in place is known as the complex insertion loss of the sample; its modulus being the sample’s transmission spectrum. The variation with frequency of the complex optical constants of the sample can be determined from the complex insertion loss [12].

The spectrometer operates in rapid scan mode with a positionally indexed sampling system and co-averaging of interferograms. The maximum path difference (double-sided) of 800 mm gives a maximum unapodised frequency resolution of 0.1875 GHz. The largest lenses in the system are 110 mm in diameter, and the system is mounted on a baseplate which is 2.0 m \( \times \) 1.8 m. The size is a consequence of the frequency resolution. The sample is located at a beam-waist with a frequency invariant 1/\(e\) amplitude half-width of 25.2 mm. Since the leaf dimensions were smaller than this, the sample beam waist was reduced to 14 mm with an aperture stop.

II. EXPERIMENTAL RESULTS

Spot-frequency measurements of leaf transmittance at 94 GHz, are shown in Figs. 2 and 3. Fig. 2 is a plot of the amplitude transmission coefficient against negative water potential for seven detached leaves from a plant of Catalpa bignonioides Walt. (Indian Bean or Southern Catalpa) after these have been inserted inside a pressure chamber. The transmittance shows the expected plateau between 0 kPa (full saturation) and -2500 kPa, which is typical in most plant–water relations studies, as well as the expected increase in transmittance at more negative water potentials.

The large scatter in the measured transmittance values is due to thickness variations between leaves and to the beam being incident on different parts of a leaf (with different thickness) between successive measurements as the leaf was placed in the pressure chamber. Smaller scatter has been observed in other experiments [13] where leaves were able to equilibrate in an osmotic solution (polyethylene–glycol) for

![Fig. 2. Transmittance against water potential for seven leaves of Catalpa bignonioides. The error bar represents errors due to the precision of the transmissometer.](image)

![Fig. 3. Transmittance changes due to natural water loss for (a) Fatsia japonica and (b) Catalpa bignonioides.](image)
Fig. 4. Transmittance changes due to natural water loss in *Fatsia japonica*.

24 h and subsequently placed in the transmissometer so that three measurements over different sections of the leaves were performed. This suggests that the discrepancies observed in Fig. 2 may be due to a pressure gradient introduced by the pressure chamber, as well as thickness variations.

A theoretical error analysis based on the Jones matrix analysis in the Appendix, results in a standard error of ±0.84% in the transmittance depicted in Fig. 2. This has been calculated after taking into account the quantization error in determining the position of the rotating grid (0.017 rad) and the detector noise equivalent power \(5 \times 10^{-10} \text{ W Hz}^{-1/2}\) for a source power of 10 mW. Detector-noise equivalent power was calculated after experimentally determining the least detectable signal and taking into account the responsivity of the detector (20 mV mW\(^{-1}\)). A detailed description of the error analysis is given in [14].

In another experiment, [Fig. 3(a)] a detached leaf of *Fatsia japonica* (Thunb.) Decne. & Planchon was placed in the transmissometer and its transmittance measured over a long period. Measurements were repeated [Fig. 3(b)] using a detached *Catalpa* leaf. The ambient temperature and relative humidity were constant to within 2 K and 3%, respectively. The results show a clear increase in transmission as the leaves lose water, the errors due to leaf placement, thickness and pressure chamber equilibration process no longer being present. As expected, the *Fatsia japonica* leaf, which has a waxy cuticle, exhibits a slower water loss rate, but it follows the same form as the early part of the *Catalpa bignonioides* curve [Fig. 3(b)].

In another experiment, a more detailed study was performed using a pair of naturally drying *Fatsia japonica* leaves. The weight (due to natural water loss) and the transmittance were measured simultaneously (Fig. 4).

The change in thickness of the second leaf (average of three measurements performed using a micrometer to an accuracy of 2 \(\mu\)m) is related to the change in weight of the first leaf indicating that there is a direct relation between the thickness variation with the cube root of the weight of the water lost during the drying period (Fig. 5).

Fig. 6 shows a broad-band measurement of transmittance for the two different leaves under various conditions. The absorption due to water increases with frequency. The absence of a channel spectrum is notable. The features at 150 and 300 GHz are due to electrical pickup. *Phormium tenax* has a greater water storage ability (thus, is more absorbing) than *Fatsia japonica*.

### III. Discussion

#### A. Relation Between Transmittance, Absorbance and Osmotic Potential in the Leaf Structure

In most higher plants and some lower plants, each cell has a large central aqueous phase, the vacuole, which occupies about 90% of its volume. The aqueous solution in the vacuole containing inorganic ions, organic acids, sugars, and amino acids as solutes, are mainly responsible for the observed attenuation of terahertz radiation. This is directly related to the complex insertion loss \(\bar{L}(k)\) measured when a specimen is inserted into the millimeter-wave beam (where \(k = \omega/c\) is the wavenumber, \(\omega\) is the angular frequency, and \(c\) the speed of light in free space). The complex insertion loss can further be related to the complex transmission coefficient \(\bar{\tau}(k)\) of the specimen

\[
\bar{L}(k) = \bar{\tau}(k)e^{-ikd} \tag{2}
\]
the factor $e^{-i\beta d}$ arising because the specimen replaces a length $d$ of air in the arm of the interferometer.

At the cellular level, assuming elastic extension of cell walls, the effect of change in the difference in pressure $\Delta P$ between the contents of a spherical cell and the environment results in a change $\Delta d$ in the linear dimension $d$ of the sample, which is directly related to its change in volume $\Delta V/V = (\Delta d/d)^3 = \Delta P/\varepsilon_e(P)$ where $\varepsilon_e(P)$ is the volumetric elastic modulus of the cell (a similar expression may be derived for the longitudinal extension of the palisade cells). The volumetric elastic modulus is a function of turgor pressure [15] $\varepsilon_e(P) = \varepsilon_m[(\varepsilon_m - \varepsilon_0)e^{-\mu P}]$ where $\varepsilon_m$ is the maximum value, $\varepsilon_0$ is the value at zero turgor pressure, and $\mu$ is an experimentally determined constant. At low pressures, $\varepsilon_e$ can be approximated by the linear relation $\varepsilon_e(P) = \varepsilon_0 + bP$ and at higher pressures $\varepsilon_e \approx \varepsilon_m$. A change $\Delta P$ in a spherical sample leads to a newly measured magnitude of the complex insertion loss given from

$$\hat{L}(k) = |\hat{L}(\omega)| \exp\left(-\frac{a(k)\Delta d}{2}\right) \left(\frac{\Delta P}{\varepsilon_e(P)}\right)$$  \hspace{1cm} (3)$$

where $a(k)$ is the power absorption coefficient (Np cm$^{-1}$) of the specimen. Equation (3) can be extended to the tissue level, as it is assumed that under steady-state conditions, the linear dimensions of the leaf are modified uniformly so that no turgor gradients occur between adjacent cells (perfect osmometer behavior). Experimental results using leaf strips or discs immersed in osmotic solutions of different concentrations quoted in the literature [16] justify this assumption. In this case, the complex insertion loss can be related to a change in thickness from

$$\hat{L}(k) = |\hat{L}(\omega)| \exp\left(\frac{-a(k)\Delta d}{2\varepsilon_e(P)}\right)$$  \hspace{1cm} (4)$$

where $\zeta$ is a macroscopic parameter related to the experimentally determined $\Delta d/d$ ratio and $\varepsilon_e$ is the volumetric elastic modulus of the leaf tissue.

Most chemists use quantities such as the natural molar absorption (or extinction) coefficient $\varepsilon_{mn}$ (Np L mol$^{-1}$ cm$^{-1}$) and concentration $C$ (mol L$^{-1}$) in order to describe the spectral absorption bands in a solution. It can be shown that the power absorption coefficient for a mixture of species is

$$a(k) = \sum_j \varepsilon_{mn_j}C_j$$  \hspace{1cm} (5)$$

where $\varepsilon_{mn_j}$ are the molar absorption coefficients of chemical species $j$ and $C_j$ is the concentration of solutes.

One could define an effective complex refractive index of the leaf $n(k) = n + in'(k)$ where $n(k)$ is related to the absorption coefficient by

$$\kappa(k) = \frac{\alpha(k)}{2k}$$  \hspace{1cm} (6)$$

In the case of pure water, typical values of the imaginary part of the complex refractive index can be found from published data [17]. The assumption of an effective refractive index implies that the ensemble of approximately planar membrane segments of the cells is isotropic in a macroscopic sense since all membrane orientations occur with equal probability and, thus, there is no need to treat the leaf as a multilayered structure. It can be shown [12] that the complex refractive index of a sample is related to the measured complex insertion loss by

$$\hat{L}(k) = -\frac{4\hat{n}}{(1+\hat{n})^2} - \frac{e^{i\kappa(\omega)\Delta d}}{1 - ((1 - \hat{n})/(1 + \hat{n}))^2} e^{2ik\kappa d}$$  \hspace{1cm} (7)$$

where $n$ and $k$ are the real and imaginary parts of the refractive index of the sample with contributions from all the chemical species present, and $d$ is the thickness of the sample. Although (7) cannot be solved explicitly for $\hat{n}(k)$ in terms of $\hat{L}(k)$, an iterative procedure based on the complex secant method may be used [12]. Equation (7) arises from an infinite sum of partial waves inside the sample resulting from multiple reflections from the air–sample interfaces. If such reflections are significant, they result in a series of interference fringes, known as a channel spectrum, appearing in the transmission spectrum. Moreover, inspection of the broad-band transmittance measurements in Fig. 6 shows no evidence of channel spectra. However, inspection of the broad-band transmittance measurements in Fig. 6 shows no evidence of channel spectra. Moreover, if one uses (7) to simulate transmission spectra for samples of typical leaf thickness using published data for the complex refractive index of water, one finds that the multiple reflections and channel spectrum are quenched by absorption in the water. In this case, the measured complex insertion loss can be safely assumed to arise solely from a single-pass transmission through the leaf and closed-form expressions for the effective complex refractive index can be found. The real and imaginary part of the complex refractive index of the sample are then related to the complex insertion loss from

$$n(k) = 1 + \frac{1}{kd}\arctan(\hat{L}(k)) + 2\pi\nu$$  \hspace{1cm} (8a)$$

$$\kappa(k) = \frac{1}{kd}\ln\left[\frac{4n(k)}{(1 + n(k))^2} \left|\frac{\hat{L}(k)}{\hat{L}(k)}\right|\right]$$  \hspace{1cm} (8b)$$

where $\nu = 1, 2, \ldots$ etc. The imaginary part of the complex insertion loss is directly related to the phase measured using the transmissometer.

**B. Errors Related to the Estimation of the Complex Insertion Loss Function**

1) **Thickness, Temperature and Concentration Related Errors:** These errors can be further divided into errors due to thickness measurements, errors due to temperature variation as related to changes in leaf thickness and complex refractive index of the solutes in the vacuoles, and errors due to nonnormal incidence of the beam on the sample.

Errors due to thickness measurements may be minimized using an appropriate displacement transducer after averaging a number of readings over the surface of the leaf exposed to the beam. Errors due to temperature variation as related to changes in leaf thickness are difficult to quantify, as there are no current papers in the literature that quantitatively relate changes in the volumetric elastic modulus of a cell or the leaf tissue directly with temperature. Errors due to temperature...
variation as related to changes in the complex refractive index of water have only been systematically investigated for pure water [18]. Detailed measurements from 180 to 420 GHz in temperatures varying from 283 to 313 K have shown a change in the absorption coefficient of water of approximately 1 Np \cdot cm^{-1} \cdot K^{-1}. The complex refractive index of some aqueous solutions has also been reported to vary with concentration [19], and this may result in another source of error due to changes in the accumulation of solutes in the vacuoles at periods of water stress (osmoregulation). It follows that results of tissue-absorbance measurements should, therefore, clearly distinguish between changes due to a change in thickness and due to a change in the complex refractive index of the solution in the cells. This effect could be explored using the procedure outlined in the previous section using (8a) and (8b).

Nonnormal illumination of the sample leads to a systematic error due to the larger path length through the sample. This results in an overestimation of the absorbance and an under-estimation of the value of the effective refractive index. For a leaf sample of thickness \(d\) having average effective refractive index \(n\), the internal path length \(d'\) traveled by the radiation at nonnormal incidence is [20]

\[
d' = \frac{d}{\sqrt{1 - \sin^2 \theta_i / \pi^2}}. \tag{9}
\]

This error has a direct effect on the measured magnitude of the complex insertion loss \([L'(k)]\)

\[
|L'(k)| = |\hat{L}(k)| e^{-a(k)\cdot d' - \theta / 2} \tag{10}
\]

but is negligible for all but extreme angular misalignments. Using typical values for leaf thickness and published data on the optical constants of water shows that a 10° misalignment results in, at worst, an error of 0.6% in the complex insertion loss.

2) Analysis of Pseudocoherence Effects in DFTS Assuming a Plane-Wave Beam Incident on the Sample: The phenomenon of pseudocoherence is the quantitative description of the loss of interferometric modulation in an observed interferogram as a function of sample surface roughness and frequency (or wavenumber). Different rays traveling through the leaf destroy the coherence as they travel through different path lengths. Birch [21] showed that the complex factor \(\hat{f}(k)\) by which the ideal complex spectrum \(\hat{S}(k)\) is degraded by the nonperfect geometry of the sample is

\[
\hat{S}_N(k) = \hat{f}(k) \hat{S}(k) \tag{11}
\]

where

\[
\hat{f}(k) = \frac{1}{N} \left[ \left( \sum_{j=1}^{N} \cos k(\bar{n} - 1)\delta_j \right) - i \left( \sum_{j=1}^{N} \sin k(\bar{n} - 1)\delta_j \right) \right] \tag{12}
\]

and \(\delta_j\) is the linear thickness variation after dividing the specimen into \(N\) regions. We have modified (12) to take account of single-pass transmission through the specimen. Equation (11) is directly related to the complex insertion loss. The degradation factor results in underestimating the true complex insertion loss of the specimen

\[
\hat{L}_{pe}(k) = \hat{f}(k) \hat{L}(k) \tag{13}
\]

where \(\hat{L}_{pe}(k)\) is the measured insertion loss incorporating pseudocoherence effects. When \(\hat{f}(k) = 0\), a complete loss of modulation occurs and the complex insertion loss of the specimen cannot be determined.

In addition, it is possible to write an expression relating the true complex transmission coefficient of the specimen with the measured complex insertion loss when pseudocoherence is present as follows:

\[
\hat{t}(k) = \frac{\hat{L}_{pe}(k)}{\hat{f}(k)} e^{ikd}. \tag{14}
\]

Furthermore, pseudocoherence leads to a measured absorption coefficient \(\alpha'\) significantly different from the actual absorption coefficient \(\alpha\) of the specimen, which is related to the thickness of the specimen and the operating wavelength

\[
[\alpha'(k) - \alpha(k)]d = \ln \frac{1}{|\hat{f}(k)|}. \tag{15}
\]

This relation can further be written in terms of the true complex transmission coefficient of the specimen and the measured complex insertion loss from

\[
\alpha'(k) = \alpha(k) - ik \ln \frac{|\hat{f}(k)|}{|\hat{L}_{pe}(k)|}. \tag{16}
\]

From (15), it can be concluded that the difference in the measured absorbance due to pseudocoherence effects increases rapidly for thin specimens (such as leaves) and can become a significant error in the determination of the absorbance in the
case of a dry leaf. Fig. 7 represents theoretical estimates of the frequencies for which the degradation function (12) results in a complete loss of the observed complex spectrum after assuming that the average refractive index of the specimen \((\overline{n} = 1.5)\) does not change with frequency, with linear variations \((\overline{n} - 1)\delta_{\text{max}}\) of 50 \(\mu\text{m}\) and 100 \(\mu\text{m}\) after assuming \(N = 100\). As expected, the surface roughness (expressed as a linear thickness variation \(\delta_{j}\)) becomes more prominent at higher frequencies and, therefore, investigations of absorbance of leaf water content should be restricted to lower frequencies (below 1 THz) to minimize pseudocoherence errors. In practice, these theoretical estimates may deviate from the actual effects of pseudocoherence because of a nonlinear thickness variation \(\delta_{j}\) as many leaves are smooth in most areas and veined in others; the results here represent a worst-case scenario. Furthermore, the variation of the average effective refractive index of water with frequency must be taken into account. The circles in Fig. 7 represent simulated values of the pseudocoherence function and its effect on the absorption spectrum from measured values of the refractive index of water extracted from the literature [17].

Since pseudocoherence effects are also related to the sample thickness, the absorption error-thickness product \(k(\overline{n} - 1)\delta_{\text{max}}\) is shown in Fig. 8 after assuming a linear thickness variation \((\overline{n} - 1)\delta_{\text{max}}\) in the leaf surface of 50 \(\mu\text{m}\) (shifts to shorter wavelengths of these peaks occur for smaller thickness variations). Points based on measured values for the refractive index of water extracted from the literature [17].

Fig. 8. The absorption error-thickness product plotted against the dimensionless triplet product \(k(\overline{n} - 1)\delta_{\text{max}}\) for constant refractive index with frequency with \((\overline{n} - 1)\delta_{\text{max}} = \pm 50 \mu\text{m}\). The data points are based on measured values from [17] for the refractive index of water.

IV. CONCLUSION

In this paper, a novel technique suitable for noninvasive measurements of leaf water content has been suggested. This is based on measurements of the change in the complex insertion loss observed at terahertz frequencies. Transmittance measurements correlate well with measurements of leaf thickness and water content and the discrepancy in the results shown in Fig. 2 highlight the importance of leaf placement to the beam and the need for simultaneous measurements of leaf thickness. The errors related to the estimation of the complex insertion-loss function have been discussed and the immunity of the measurements to angular misalignments has been shown. Pseudocoherence effects in the leaf structure due to surface irregularities are not masked by the variation of the refractive index of water with frequency, but the resulting degradation of the observed spectrum is insignificant at frequencies below 1 THz. The technique could be used to determine the number of absorbers (water molecules) from measurements of the sample’s thickness and its complex insertion loss.

APPENDIX

JONES MATRIX ANALYSIS OF THE NULL-BALANCE TRANSMISSOMETER

Each element in an optical system can be described by a Jones matrix, which relates the polarization state of the emergent beam to that of the incident beam, as described by a column vector \([E_V E_H]\), where \(E_V\) and \(E_H\) are the vertical and horizontal linearly polarized components of the \(E\)-vector. The Jones matrices for reflection from and transmission through a wire grid with wires at an angle \(\theta\) to the vertical component (as seen from the direction of incidence) are, respectively,

\[
R(\theta) = \begin{bmatrix} \cos^2 \theta & -\cos \theta \sin \theta \\ \cos \theta \sin \theta & \sin^2 \theta \end{bmatrix}
\]

and

\[
T(\theta) = \begin{bmatrix} \sin^2 \theta & -\cos \theta \sin \theta \\ -\cos \theta \sin \theta & \cos^2 \theta \end{bmatrix}.
\]

Reflection from a plane mirror is described by \(M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\) and transmission through a sample of thickness \(d\) and refractive index \(n\) by \(S = |R|e^{jkd/n}\). The effect of a train of optical elements can be determined by multiplying together the appropriate sequence of matrices. Where beams are combined, the resultant is determined by adding the individual beam vectors.

For the transmissometer, the beam in the reference arm is given by

\[
C_1 = R(-45^\circ)M e^{jkd}M M T(\theta) M R(45^\circ) T(\theta^\prime) \begin{bmatrix} 0 \\ 1 \end{bmatrix}
\]

where the variable distance \(\delta\) is controlled by the moveable roof mirror and the angle \(\theta\) is controlled by the rotatable grid. The beam in the sample arm is given by

\[
C_2 = T(45^\circ) M S M T(45^\circ) T(\theta^\prime) \begin{bmatrix} 0 \\ 1 \end{bmatrix}.
\]

The output at the detector is then \(D = T(90^\circ)^\dagger(C_1 + C_2)\). It is found that a null at the detector is obtained when \(\delta = d/n\) and \(|\theta| = \frac{1}{2} \sin^{-1} \gamma\). The reference grid transmits all of the incident polarization when \(\theta = -45^\circ\) and gives a null when \(\theta = -45^\circ - \gamma\) where \(\gamma\) is half the angle between the adjacent nulls. Thus, we find \(|\theta| = \cos^2 \gamma\).
REFERENCES


Sillas Hadjiloucas (M’94) was born in Athens, Greece, in 1966. He received the B.Sc. (honors) and M.Phil. degrees from the University of Leeds, Leeds, U.K., in 1989 and 1992, respectively, and the Ph.D. degree from the University of Reading, Reading, U.K., in 1996.

In 1993, he joined the Instrumentation Research Group, Department of Cybernetics, University of Reading, Reading, U.K. Since October 1997, he has been an EC TMR (Training and Mobility of Researchers) Post-Doctoral Research Fellow, working on terahertz instrumentation as part of the International Terahertz Action (INTERACT) Project. He has authored or co-authored several articles related to feedback, instrumentation, optics, biology, and terahertz measurement techniques.

Dr. Hadjiloucas is a member of the Institute of Biology (MBiol CBiol) and the Optical Society of America, and is a graduate member of the Institute of Physics (GradInstP). In 1996, he was appointed member of the Technical Advisory Committee for Plastic Optical Fibers and Applications (Paris, France).

Lucas S. Karatzas (M’95) was born in Athens, Greece, in 1967. He received the B.Sc. (honors) degree in cybernetics and control engineering with mathematics and the Ph.D. degree from the University of Reading, Reading, U.K., in 1990 and 1994, respectively. During his undergraduate and postgraduate studies, his areas of interest included the development of instruments using fiber optics and interferometry.

Since 1994, he has been a Research Fellow at the University of Reading, researching instrumentation and techniques, for the generation, detection, and analysis of terahertz-frequency electromagnetic radiation. He has authored or co-authored several publications on optical instrumentation methods using feedback configurations.

Dr. Karatzas is a member of the Institute of Physics (MInstP, CPhys).

John W. Bowen was born in Malvern, Worcestershire, U.K., in November 1963. He graduated in physics from Queen Mary College, University of London, London, U.K., in 1985, and received the Ph.D. degree in 1993 for research into techniques for wide-band millimeter-wave spectrometry.

Since 1993, he has been a Lecturer in the Department of Cybernetics, University of Reading, Reading, U.K., where he heads the Instrumentation Research Group. He is currently completing a book Terahertz Sensing and Measurement Systems (London, U.K.: Chapman & Hall, to be published). His research interests include quasi-optical systems design, millimeter and submillimeter-wave spectrometry and device characterization, solid-state noise sources and terahertz antennas.

Dr. Bowen is a member of the Terahertz Integrated Technology Initiative Network (TINTIN), U.K., and the Europe-wide EC-funded International Terahertz Action Network (INTERACT). He is a member of the organizing committee of the SPIE Conference on Terahertz Spectroscopy and Applications, to be held in Munich in June 1999. He was awarded the 1989 U.K. National Physical Laboratory Metrology Award for his suggestion for a new wide-band solid-state noise source for millimeter-wave spectrometry.