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Cement & Concrete Composites 28 (2006) 349–359
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

A methodology for determining complex permittivity of construction materials based on transmission-only coherent, wide-bandwidth free-space measurements

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Abstract

An integrated methodology for determining the unique combination of complex permittivity based on measured transmission coefficient and time difference of arrival (TDOA) information in free-space measurements is proposed. The methodology consists of an estimation procedure of the real part of complex permittivity based on TDOA, and a root-searching procedure based on parametric system identification (SI) together with an error sum of squares (SSE) criterion. Generally, non-unique combinations of dielectric constant and loss factor are encountered when lossy or low-loss materials are measured and the proposed methodology is aimed at the determination of unique combinations of dielectric constant and loss factor for such materials. The proposed methodology is validated by measurements of several materials with known dielectric properties. The estimated complex permittivity values for Teflon, Lexan, Bakelite, and concrete are in good agreement with those reported in the literature. The method has potential for in-situ measurement of dielectric properties for construction materials. Applicability and limitations of the methodology are discussed.

Keywords: Complex permittivity; Transmission coefficient; Radar; Time difference of arrival; Parametric system identification

1. Introduction

Dielectric properties (complex permittivity) of materials have received increasing attention along with the use of electromagnetic (EM) waves (radar/microwave) in the investigations of material and structural assessment. Dielectric properties of a material correlate to other material characteristics and may be used to determine properties such as moisture content, bulk density, bio-content, chemical concentration, and stress–strain relationship. Such knowledge can be utilized for research and application in food science, medicine, biology, agriculture, chemistry, electrical devices, defense industry (security), and engineering. In civil engineering, for example, dielectric properties of construction materials such as concrete are the key information to the non-destructive testing (NDT) of civil structures using radar techniques [20,21]. However, the utilization cannot be accomplished without the aid of a reliable methodology for the measurement and determination of dielectric properties.

Up to the present, several experimental methods have been applied to the measurement of dielectric properties of a material. These methods include parallel plate capacitor technique [1], resonator/oscillator technique [2], transmission line technique [3–6], and free-space technique [7–11]. Although each technique has its own features and constraints, among these, the free-space technique appears to be more applicable for in-situ measurements. In free-space measurements, transmission and reflection coefficients (which can be real or complex) of the material under test can be measured, depending on the measurement scheme. However, the use of reflection coefficients may suffer from surface condition of the material in high frequency ranges. Implementation of complex transmission coefficients in determining dielectric properties appears feasible.

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0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2006.02.004

However, a unique determination of the complex permittivity may not be directly accomplished with the availability of complex transmission coefficient (real and imaginary parts). This is because one cannot explicitly derive relationships between the real and imaginary parts of the complex permittivity with the respective real and imaginary parts of complex transmission coefficient. Typical approach to solve such problems is the use of root-searching or optimization techniques, which search for the most reasonable (optimal) combination within given range of variables. An error evaluation criterion is usually needed in the object function, which serves as the basis for determining the optimal solution. For lossless materials, a unique optimal combination can be expected after the application of root-searching techniques at single frequency. However, for lossy or low-loss materials such as concrete, multiple combinations of real and imaginary parts of complex permittivity for the same transmission coefficient at single frequency are observed [8,12–14].

The objective of this paper is to propose an integrated methodology for determining unique combinations of complex permittivity using transmission coefficient and the time difference of arrival (TDOA) information (both obtained from free-space measurement) for low-loss materials. Experimental measurements are conducted in coherent condition which suggests the proportionality between the signal-to-noise ratio (SNR) and the length of signals. The coherent condition provides a consistent phase from measurement to measurement. In the experimentation, frequency domain measurements are made through a network analyzer using frequency bands ranging from 8 GHz to 18 GHz. In this paper, first, definition of dielectric properties is given followed by a brief review of current measurement techniques for determining these properties. A detailed description of the proposed methodology is then provided. Validation of the proposed methodology is performed by comparing the determined dielectric properties of Teflon, Lexan, Bakelite with reported values. Further application of the method is given by measurements on Portland cement concrete (PCC) slabs and a glass fiber-reinforced polymer (GFRP) sheet. Experimental set-up as a basis for the measurements is described. Implementation issues and limitations of the methodology are discussed.

2. Definition of dielectric properties

Dielectric properties of materials can be interpreted both macroscopically and microscopically. From the macroscopic point of view they are the relationship between the applied electric field strength $\overline{E}$ (V/m^2) and the electric displacement $\overline{D}$ (C/m^2) in the material. Microscopically, dielectric properties represent the polarization ability of molecules in the material corresponding to an externally applied electric field $\overline{E}$. In engineering practices, generally, macroscopic descriptions of dielectric properties of materials are used. In this paper, such a characterization of dielectric properties of a material is implemented by the use of a scalar, effective complex permittivity, ε_e^*, to account for EM features (polarization and capacitance, dielectric losses, and conductivity) of the material:

$$\varepsilon_e^* = \varepsilon_e' - j\varepsilon_e'' = \varepsilon^* + \frac{\sigma^*}{j\omega} = \left(\varepsilon' + \frac{\sigma''}{\omega}\right) - j\left(\varepsilon'' + \frac{\sigma'}{\omega}\right) \tag{1}$$

where ε_e' is the real part of ε_e^* and represents the ability of a material to store the incident EM energy through wave propagation, ε_e'' is the imaginary part of ε_e^* and represents the degree of EM energy losses in the material, j is the imaginary number; $\varepsilon^* = \varepsilon' - j\varepsilon''$ is the complex permittivity (F/m), $\sigma^* = \sigma' + j\sigma''$ is the complex electric conductivity (Ω/m), and $\omega = 2\pi f$ is the angular frequency (rad/s). The dimensionless relative permittivity ε_r^* is more frequently used, which is defined as

$$\varepsilon_r^* = \frac{\varepsilon_e^*}{\varepsilon_0} = \frac{\varepsilon_e' - j\varepsilon_e''}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r'' \tag{2}$$

where ε_0 is the permittivity of free space and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m. The real part of the relative permittivity is known as dielectric constant and the imaginary part as loss factor. The ratio between the loss factor and the dielectric constant is called loss tangent. For dielectric materials, $\varepsilon_r'' \geqslant 0$ and $\varepsilon_r' \gg \varepsilon_r''$

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{3}$$

Dielectric constant and loss tangent are functions of measurement frequency, material homogeneity and anisotropy, moisture, and temperature in the material. Various measurement techniques are available for the experimental determination of dielectric properties. A brief review of current techniques is provided in the next section.

3. Review of current measurement techniques for dielectric properties

Current measurement techniques for dielectric properties of materials are based on the concept of impedance in which complex permittivity and complex permeability are involved. The material is modeled as a dielectric and the measurements can be made using different techniques in order to calculate the dielectric properties of the material. These techniques are briefly described as follows.

3.1. Capacitor model—parallel plate capacitor technique

With this technique, the complex permittivity of materials is measured using a perfect capacitor model. The specimen is placed between two parallel plates made of perfect conductors, and a uniform electric field over a large volume of space is generated [1]. Parallel plate capacitor technique requires the specimen to possess flat surfaces on its two sides contacting the two parallel plates. The technique is more applicable for a laboratory rather than an in-situ material characterization.

3.2. Resonator/oscillator model—resonate cavity technique

Resonate cavity technique is suggested by the American Society for Testing and Materials (ASTM) [15] as the ASTM D2520 method. Baker-Jarvis et al. [2] performed measurements of the dielectric properties of low-loss materials with loss tangent less than 0.005. The method employs closed and open cavity configurations in which resonant EM responses are measured from the material as a basis for determining the real and imaginary parts of the complex permittivity. Resonate cavity technique provides more accurate results than broadband techniques but its results are for one frequency, thus requiring a significant measurement effort when a wide range of frequency response is to be derived. Additionally, with this method one cannot measure sample sizes greater than the cavity of the resonator.

3.3. Transmission line model

Open-ended coaxial dielectric probe technique. Coaxial dielectric probe technique is basically a cut-off section of transmission line, and the material is measured by placing the probe on its machined flat surface. The EM fields at the end of the probe change when the probe contacts the material, and permittivity can be computed from the measured reflection signal [6]. Coaxial probe technique requires an intimate contact between the probe and the specimen to eliminate the measurement error induced by air gap. Application of the technique requires certain conditions with respect to the surface roughness and thickness of the material. For example, Arai et al. [4] suggested that the specimen surface roughness should be less than 0.5 μm to minimize the air gap error.

Rectangular waveguide technique. Waveguide technique is one of a class of two-port measurement (transmission line) techniques. A sample of the material needs to be machined to fill in the contact area of the waveguide, and the reflection from and transmission through the material is measured. The complex relative permittivity ε_r^* and complex relative permeability μ_r^* of the specimen is determined using the formula provided by Nicholson and Ross [3]. Waveguides can only operate in designed frequency bands associated with certain wave propagation modes. Several different samples are needed when the measurement is conducted over a large frequency range. Inaccuracy in the measurement may occur due to the air gap between the waveguide and the specimen, and the dimensions of the specimen [5]. Waveguide technique can be tedious in terms of sample preparation when the designated frequency band is not available in advance.

3.4. Free-space technique

Free-space technique is non-contact and non-destructive. It requires little or no sample preparation. With this technique, broadband characterization of isotropic or anisotropic materials under various incident angles and polarizations can be made. The free-space technique can be further categorized into reflection–transmission [7], reflection-only [8,11], and transmission-only [9] methods, depending on the experimental set-up.

Estimation of dielectric properties based on reflection data will encounter potential difficulties when the radar operates in high frequencies. For example, multiple reflections occurring at boundaries between layers in multilayered systems need to be handled, and the surface condition of the material becomes crucial for wave reflection in high frequencies. Such difficulties can be avoided by the use of transmission coefficient in the estimation of dielectric properties.

However, as mentioned in the introduction section of this paper, the use of transmission coefficients cannot uniquely determine the complex permittivity of lossy or low-loss construction materials such as concrete. Therefore, for such materials, an improved methodology which contains an estimation procedure for the real part of complex permittivity together with a root-searching procedure with minimum estimation error in transmission coefficients is needed. In what follows, such a methodology is proposed and described as a basis for predicting complex permittivity.

4. Methodology

This methodology consists of two main components: (1) an estimation procedure of the real part of complex permittivity based on the TDOA information, and (2) a root-searching procedure of possible combinations of real and imaginary parts of complex permittivity based on parametric SI and SSE criterion. In this section, a theoretical representation of transmission coefficient which is derived from EM wave theory is introduced. The estimation procedure for the real part of complex permittivity using TDOA along with the use of parametric SI and SSE criterion is also described. The overview of the methodology is illustrated in Fig. 1.

4.1. Theoretical representation of transmission coefficient

The EM wave transmission analysis is based on theoretical transmission coefficients for a two-dimensional model for EM uniform plane wave propagation through a dielectric medium proposed by Kong [16] (Fig. 2). By solving Maxwell's equations and applying energy conservation principles with appropriate dispersion relations for the particular case in hand, the expression of the complex transmission coefficient T^* for transverse electric (TE) waves in normal incidence condition is given as follows:

$$T^* = \frac{4e^{j(k_{1z}-k_{0z})d_1}}{(1+p_{01})(1+p_{10})(1+R_{01}R_{10}e^{j2k_{1z}d_1})} \tag{4}$$

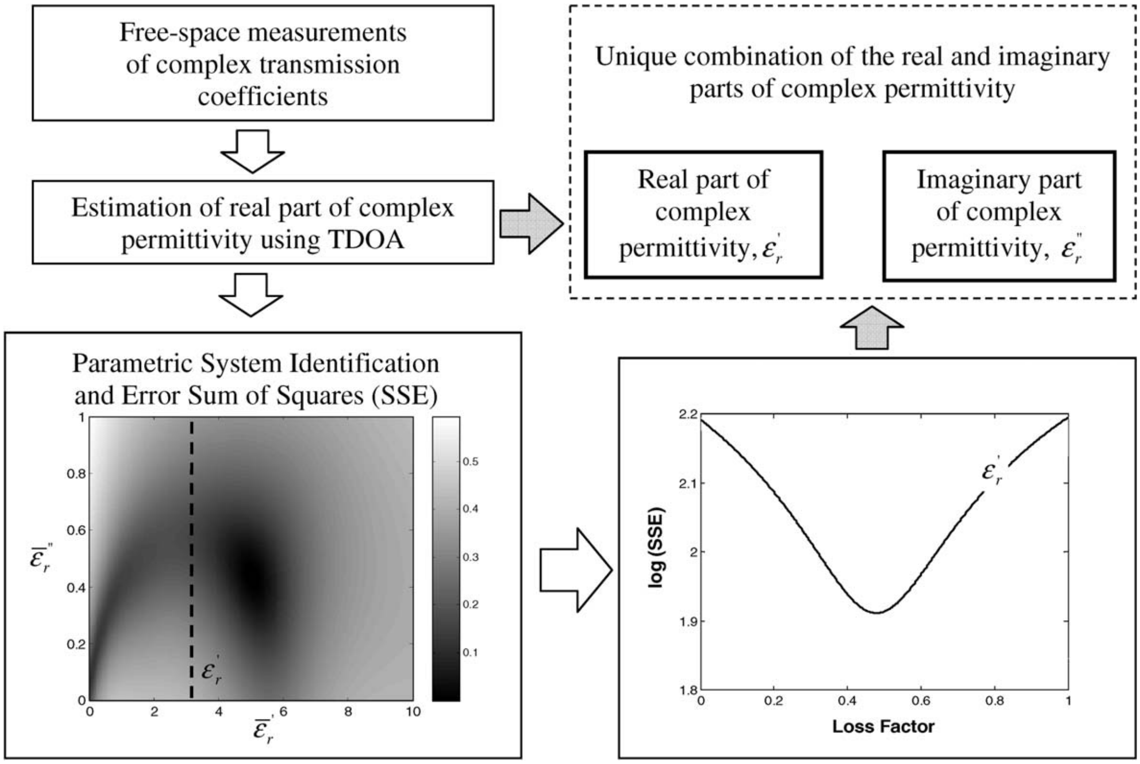

Fig. 1. Overview of the proposed methodology.

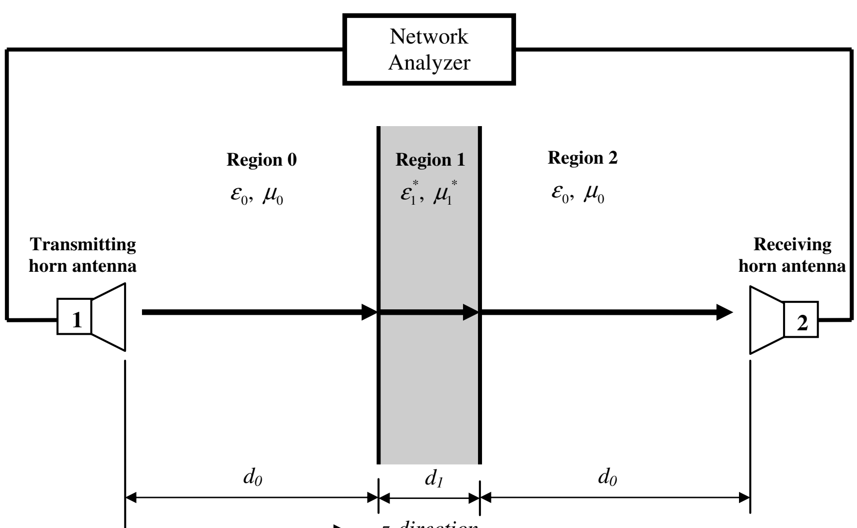

Fig. 2. The two-dimensional model for EM wave transmission analysis.

where $k_{0z} = \omega\sqrt{\varepsilon_0\mu_0}$, $k_{1z} = k_{0z}\sqrt{\mu_r^*\varepsilon_r^*}$, $p_{01} = \frac{k_{1z}}{k_{0z}} = \frac{1}{p_{10}} = \frac{\mu_0 k_{1z}}{\mu_1^* k_{0z}}$, $R_{01} = \frac{1-p_{01}}{1+p_{01}}$, d_1 = thickness of the specimen, μ_0 = permeability of free space ($4\pi \times 10^{-7}$ H/m), μ_r^* = complex relative permeability of the specimen, ε_0 = permittivity of free space (8.85×10^{-12} F/m), $\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''$ = complex relative permittivity of the specimen where ε_r' and ε_r'' are its real and imaginary parts, respectively. The EM wave propagation through a dielectric specimen is modeled as a two-dimensional problem. The use of this model is justified by the choice of an appropriate experimental set-up, in which uniform plane wave conditions are achieved by satisfying the far-field condition. Additionally, the assumption of material homogeneity in the theoretical model leads to the description of dielectric properties for the bulk material.

4.2. Estimation procedure based on time difference of arrival

The TDOA technique is used to estimate the dielectric constant of a low-loss (less conductive) material using experimental measurements of transmission coefficients. This technique is conceptually based on the same two-dimensional model for EM wave propagation shown in Fig. 2. Under the assumptions of normal incidence, first-peak response, and minor transmission losses, the time difference of arrival of an EM plane wave due to the presence of the specimen is [10]

$$\Delta t = \frac{d}{c}\left(\sqrt{\varepsilon_{\rm r}'} - 1\right) \tag{5}$$

where Δt constitutes the additional propagation time (time difference of arrival) between the transmitting and receiving antennas when the specimen is present compared to the measurement when the specimen is absent. The estimation of Δt is achieved by processing the measured transmission coefficient from frequency-domain to time-domain using inverse Fourier transformation. Eq. (5) can be used as a tool for assessing the dielectric constant of the specimen by estimating its time difference of arrival using a set of experimentally measured transmission coefficients. The expression of dielectric constant can be derived from Eq. (5) as follows:

$$\varepsilon_{\rm r}' = \left(1 + \frac{c \cdot \Delta t}{d}\right)^2 \tag{6}$$

The accuracy of the Δt estimation depends on the bandwidth of the signal being processed and the accurate measurement of the specimen thickness. Note that Eqs. (5) and (6) must be modified when the loss factor is significant. This estimate will be the basis for the identification of the complex permittivity that characterizes the dielectric material specimen.

4.3. Root-searching procedure based on parametric SI and SSE criterion

As noted by other research studies [8,12,14], the complex permittivity cannot be explicitly represented in terms of the transmission coefficient T^* or the scattering parameter (*S*-parameter), S_{21}^*, which is the forward transmission gain measured by the transmitting and the receiving radar antennas. Furthermore, the exact solution for the complex permittivity is not straightforward due to the multiple roots associated with Eq. (4) for lossy materials [13]. In order to resolve the problem, a root-searching procedure involving the use of parametric SI and SSE criterion is proposed. Parametric SI refers to the use of a mathematical model to characterize the behavior of a system [17], and in this application it is used to provide the theoretical estimation of transmission coefficients. Thereafter, SSE criterion is introduced for evaluating the optimal combination of complex permittivity.

Experimental measurements were conducted in coherent condition where measured complex S-parameter, S_{21}^*, equals the complex transmission coefficient, T^*. Coherent condition provides a non-distorted phase in the measurement of S_{21}^* (between antennas 2 (receiver) and 1 (transmitter)) such that amplitude attenuation within the specimen does not contribute to the measured transmission coefficient. In coherent condition, the magnitude of T^* expressed in decibel (dB), $T_{\rm dB}$, is related to S_{21}^* by

$$T_{\rm dB} = 10 \cdot \log\left(S_{21}^* \cdot \bar{S}_{21}^*\right) \tag{7}$$

where $T_{\rm dB}$ is a real number and $\bar{S}_{21}^*$ is the complex conjugate of S_{21}^*. Since it is observed from Eq. (4) that T^* is a function of measurement frequency, thickness of the dielectric specimen, and the complex permittivity (dielectric constant and loss factor), $T_{\rm dB}$ can also be expressed as

$$T_{\rm dB} = T_{\rm dB}\left(\omega, d, \varepsilon_{\rm r}', \varepsilon_{\rm r}''\right) \tag{8}$$

The measured $T_{\rm dB}$, denoted by $T_{\rm dB}^{\rm m}$, can be calculated by substituting the measured S_{21}^* into Eq. (7). Fig. 3 shows the $T_{\rm dB}^{\rm m}$ values as a function of frequency for the measured materials of Teflon, Lexan, Bakelite, GFRP, and concrete. The theoretical/predicted $T_{\rm dB}$, denoted by $T_{\rm dB}^{\rm p}$, can be calculated by substituting theoretical T^* into Eq. (7), given possible combinations of $\varepsilon_{\rm r}'$ and $\varepsilon_{\rm r}''$. Parametric SI is carried out by generating a set of $T_{\rm dB}^{\rm p}$ from the possible combinations of $\varepsilon_{\rm r}'$ and $\varepsilon_{\rm r}''$. From the possible combinations of $\varepsilon_{\rm r}'$ and $\varepsilon_{\rm r}''$, those resulting in minimum difference between $T_{\rm dB}^{\rm m}$ (measurement) and $T_{\rm dB}^{\rm p}$ (theory) will be the estimates closest to the real values.

Estimation error is evaluated using an error sum of squares (SSE) criterion. Each combination of the estimated $\varepsilon_{\rm r}'$ and $\varepsilon_{\rm r}''$ provides a corresponding SSE value, which is calculated by

$$\mathrm{SSE}\left(\varepsilon_{\rm r}', \varepsilon_{\rm r}''\right) = \sum_{i=1}^{n} \left| T_{\rm dB}^{\rm m}(\omega_i) - T_{\rm dB}^{\rm p}\left(\omega_i, \varepsilon_{\rm r}', \varepsilon_{\rm r}''\right)\right|^2 \tag{9}$$

where n is the number of frequency bands. With the assistance of SSE criterion, an error surface is generated for various combinations of $\varepsilon_{\rm r}'$ and $\varepsilon_{\rm r}''$, as shown in Fig. 4. Using the estimated dielectric constant (from TDOA) a corresponding error curve containing various combinations of loss factor can be located from the error surface, as shown in Fig. 5. The most possible loss factor is determined by selecting the one with minimum error on the curve. Hence, the root-searching procedure is accomplished.

4.4. Validation and application

In order to evaluate the predictions from the proposed methodology, experimental measurements of transmission coefficients were conducted for several materials whose dielectric properties are known from the literature. These materials are Teflon, Lexan, and Bakelite. In addition, Portland cement concrete and glass fiber-reinforced

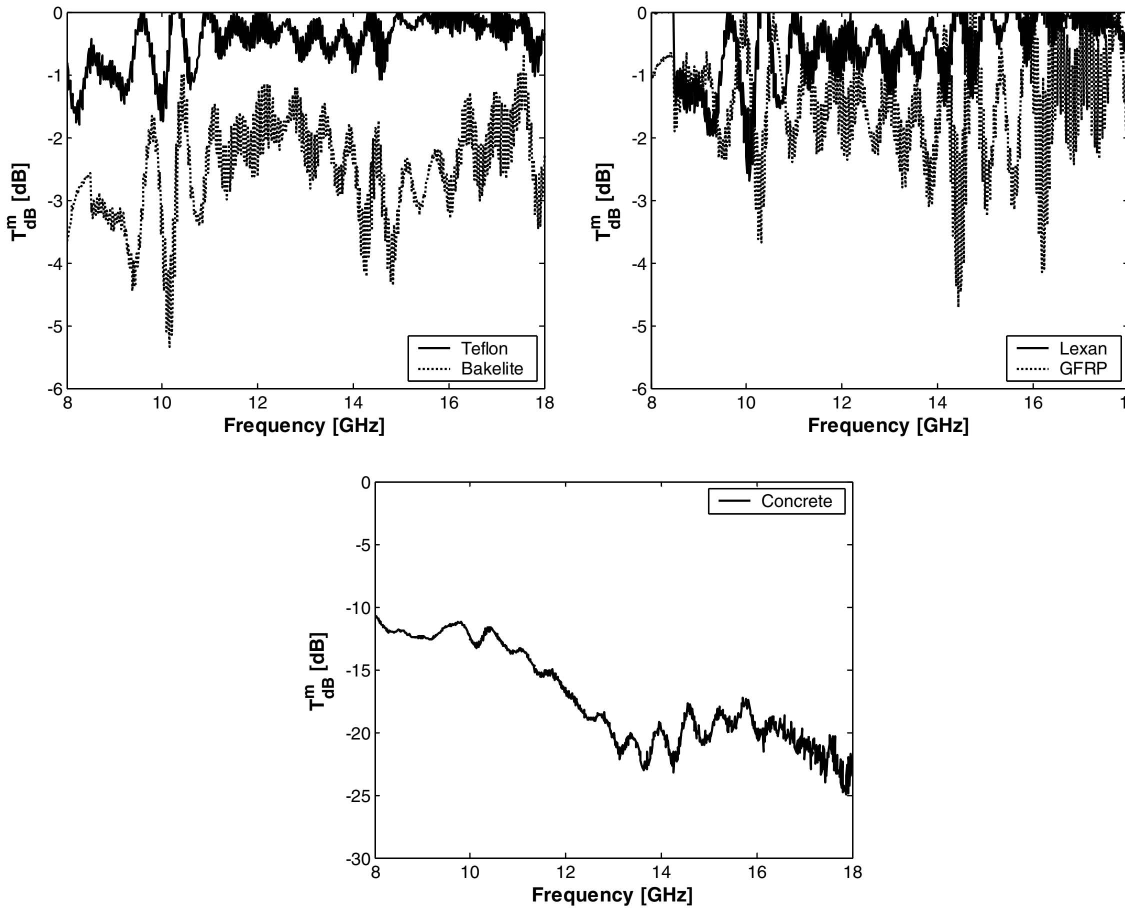

Fig. 3. Magnitude of experimental complex transmission coefficient (in dB).

polymer (GFRP) specimens were also measured as examples of construction materials.

4.4.1. Sample description and experimental configuration

For the measurements, slab-type material specimens of 305mm-by-305mm cross-section with varying thicknesses were used. The selected width and height of the specimens meet the requirement of radar measurements in the far-field condition. Table 1 shows the various specimen thicknesses for the materials used. The concrete sample was manufactured with a cement/sand/aggregate mix ratio of 1:2.25:3.2 by weight. The water-to-cement ratio (w/c) was 0.60. Portland cement of Type I was used. The uniaxial compression strength of the concrete was 24 MPa at 28 days. The glass fiber-reinforced polymer (GFRP) sample was manufactured by extruding a 305mm-by-305mm square from a unidirectional fiber woven sheet, which was then saturated with an epoxy thermoset polymer. The sample was cured for 7 days before testing.

The experimental set-up used in this study to measure the transmission of EM waves through a dielectric material involves a network analyzer and a pair of horn antennas. The network analyzer was a Hewlett Packard Model 8510C that was operated in step frequency mode. At each frequency the network analyzer performs a measurement of the complex transmission coefficient. The objective of the experiments was to obtain the complex transmission coefficients for a broad range of frequencies. A schematic of the experimental set-up is shown in Fig. 2.

Transmission measurements were collected from X-band through Ku-band (8–18 GHz) with a frequency step of 12.5 MHz. A typical set of measurements consisted of amplitudes (dB), phase angles (deg), and their corresponding frequency. Raw data was then properly calibrated using free-range measurements, which were conducted in the absence of the specimen. Far-field test conditions were ensured during measurements. The far-field condition is required to ensure that the wave front is approximately plane, which is directly related to the theoretical methodology for dielectric property characterization. Far-field conditions also minimize complex wave behavior in near-field between the horn antennas and the specimen. Considering the highest frequency of 18 GHz for the proposed experiments, it was calculated that the specimen should be placed at least 10.8 cm away from the horn antennas, and the minimum area of the slab specimens should be greater than 161.29 cm^2 for adequate illumination to satisfy the far-field condition. The applied experimental set-up meets these requirements. Direct coupling between the horn antennas is also eliminated in this experimental

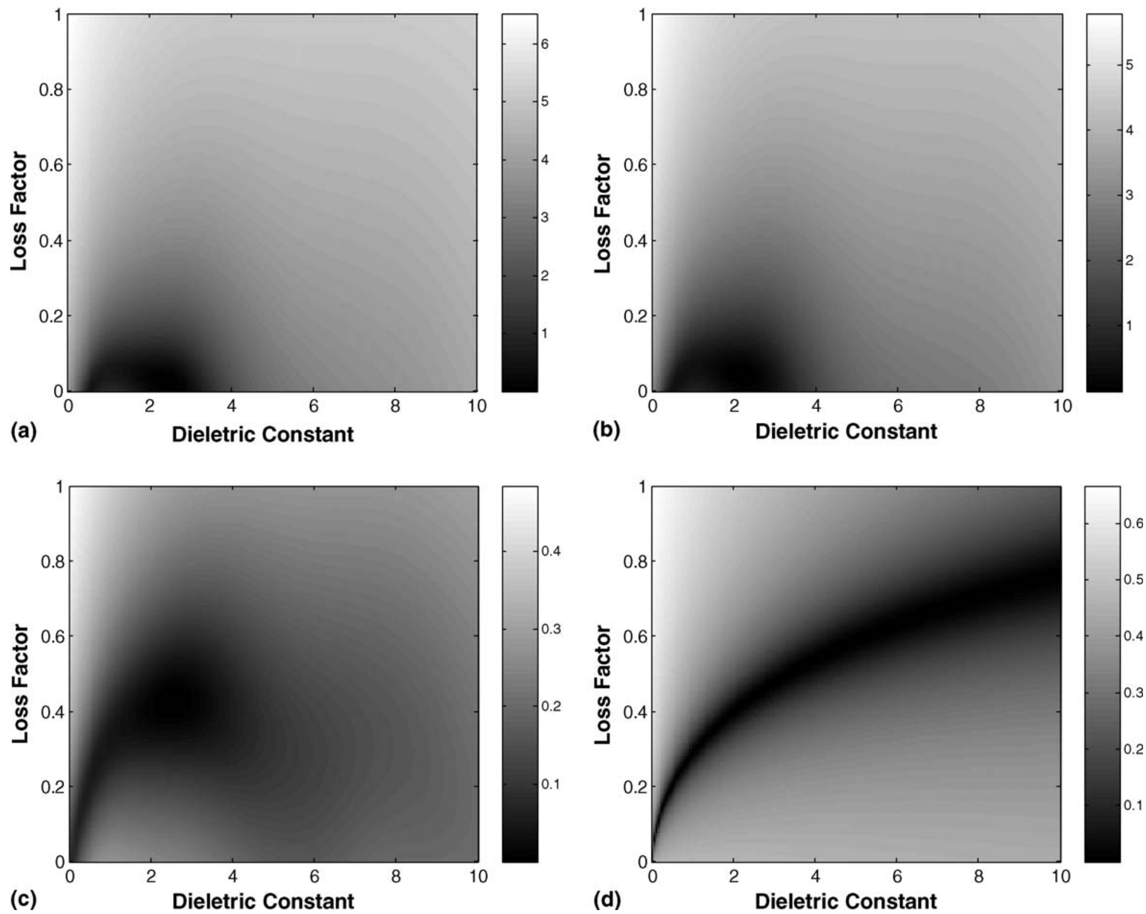

Fig. 4. The estimation error surfaces using parametric SI and SSE criterion: (a) teflon, (b) lexan, (c) bakelite, (d) portland cement concrete.

set-up due to the use of the network analyzer. The unwanted coupling between antennas is measured in free-range and stored in the phase angle information collected by the network analyzer. This information is then used in the calibration of all consequent measurements [18].

4.4.2. Estimation of the dielectric constant using TDOA

The TDOA technique was used to estimate the dielectric constant of materials under investigation from both X- and Ku-bands. After performing inverse Fourier transformation of the experimental transmission coefficient data, the time differences of arrival (Δt) for the materials considered in this study were calculated. These results are tabulated in Table 2. Using the time difference of arrival information, application of Eq. (6) yielded estimates for dielectric constants, which are also tabulated in Table 2. For the case of GFRP the TDOA technique could not provide reliable results due to the very small thickness of the specimen.

4.4.3. Root-searching results of loss factor

Following the previously described procedure, the loss factor can be found by extracting an error curve using TDOA (shown in Fig. 5) from the error surface generated by parametric SI and SSE criterion. The loss factor corresponding to the minimum SSE on the error curve is identified as the most appropriate value. The estimated loss factors thus found are given in Table 3 for the test materials.

4.5. Discussion

From the results, it is found that a unique combination of real and imaginary parts of the complex permittivity can be found through the proposed methodology for low-loss materials, such as Teflon, Bakelite, Lexan, and dried/hardened concrete in this study. The non-uniqueness problem of real and imaginary parts of complex permittivity has been resolved, and appropriate values were predicted using the integrated methodology. The method has potential for in-situ measurement of dielectric properties for construction materials.

The estimated results of complex permittivity using the proposed methodology are summarized in Table 3. The estimated dielectric constant values of Teflon, Lexan, Bakelite, and concrete are close to the reported values or within the ranges reported in the literature. It is emphasized that the values found using the proposed methodology for dielectric constants and loss factors are not expected to exactly comparable with the reported values in the literature because of the differences in frequency

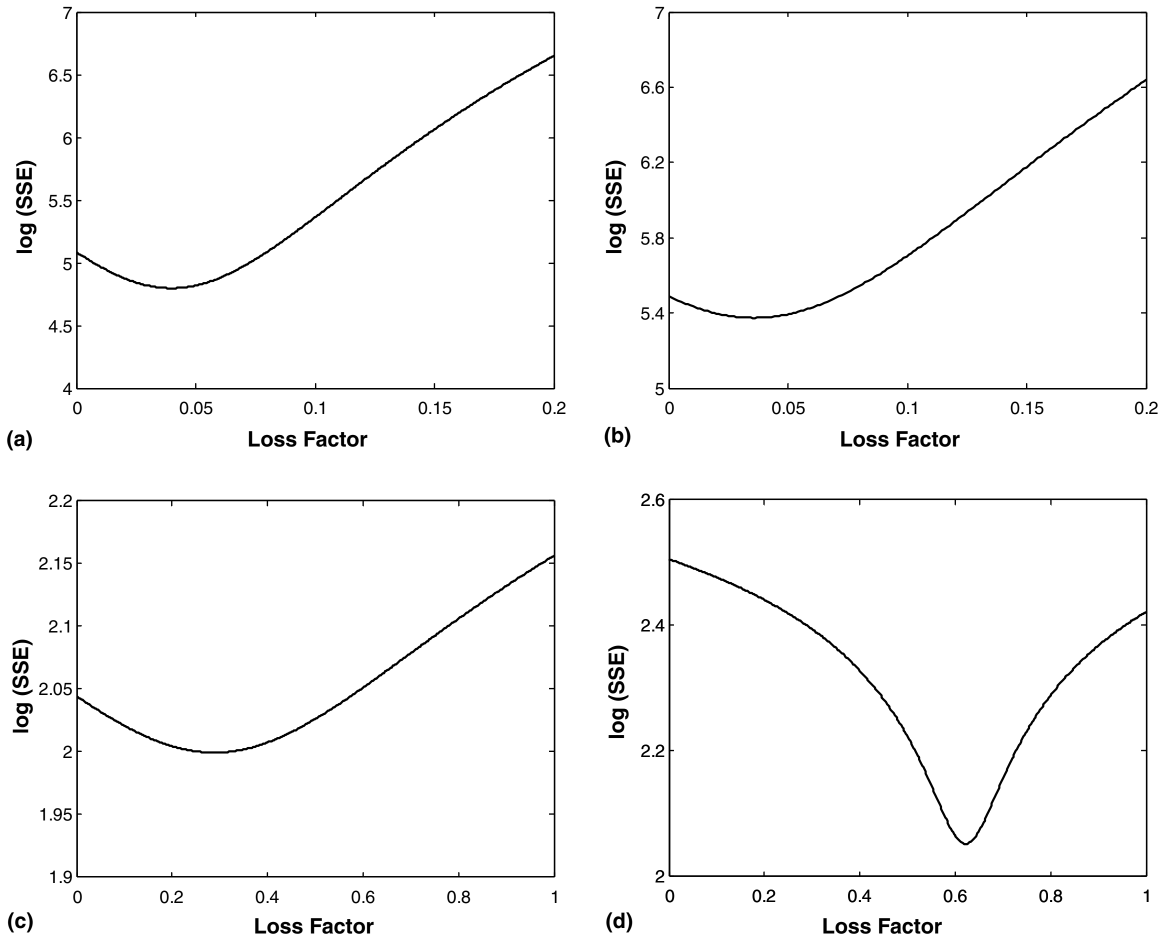

Fig. 5. Results of root-searching procedure for identification of imaginary part of complex permittivity: (a) teflon, (b) lexan, (c) bakelite, (d) portland cement concrete.

Table 1
Specimen thickness

Material	Thickness (mm)
Teflon	6
Lexan	6
Bakelite	6
Portland cement concrete	50
GFRP	1.5

Table 2
Dielectric constant estimation based on TDOA for 8–18 GHz frequency range

Material	Δt (ns)	Estimated dielectric constant
Teflon	0.007	1.79
Lexan	0.012	2.48
Bakelite	0.030	5.95
Concrete	0.235	5.69

Table 3
Characterization of complex permittivity for the test materials

Material	Estimated dielectric constant	Estimated loss factor	Dielectric constant from literature
Teflon	1.79	0.04	2.0 [19]
Lexan	2.48	0.04	2.77 [23]
Bakelite	5.95	0.28	5.0 [22]
Concrete	5.69	0.62	4.44–7.22 [20]

ranges specimen preparation, and measurement techniques. Note that in Table 3 the loss factor comparison could not be made because of the lack of information on loss factors in the literature. Also, loss factor values are generally more sensitive to measurement frequency and experimental parameters.

Effect of selected frequency bands in TDOA. TDOA estimates for the dielectric property characterization of the materials presented in this study were obtained using the entire set of measurements for the X- and Ku-bands. For practical applications of this methodology, the question arises as to what would be the optimum frequency range to provide a sound estimate for the dielectric constant. Calculations were conducted in 1 GHz, 2 GHz, 3.3 GHz,

Table 4
Estimates for dielectric constant using TDOA for different frequency ranges

Material	Frequency range (GHz)									
	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18
Teflon	1.42	5.80	1.89	1.89	2.37	1.18	1.32	2.28	2.28	2.34
Lexan	–	6.05	6.96	2.25	2.53	2.06	4.53	3.61	2.41	3.23
Bakelite	–	0.96	14.75	5.38	8.86	8.17	5.45	4.69	9.76	–
Concrete	4.80	6.03	6.64	5.30	5.01	4.66	8.04	6.76	5.99	4.47

5 GHz, and 10 GHz intervals covering the range from 8 GHz to 18 GHz to study the effect of frequency bandwidth. Table 4 presents a summary of different estimates of dielectric constant using TDOA that were calculated in 1 GHz bandwidth. The convergence of these estimate curves is evaluated by the variance shown in Fig. 6. It is observed that estimates calculated from narrow frequency bandwidths may provide poor estimates for dielectric constant. Accurate estimates using the TDOA technique require the use of wide frequency bandwidths for uniquely identifying the dielectric constant. Reliable estimation was achieved when frequency bandwidth used exceeded 3.3 GHz in our measurements. The accuracy of such estimation is critical to the subsequent determination of the loss factor.

Limitations of the use of TDOA.

(1) Effective thickness of specimen—From the results for GFRP, it is observed that the thickness of the sample affects the performance of TDOA technique. Thus, a minimum thickness limitation might apply to the accurate characterization of dielectric constant of construction materials using the proposed methodology. Our preliminary investigations indicate that measurements of specimens of 6 mm or larger would provide acceptable results.

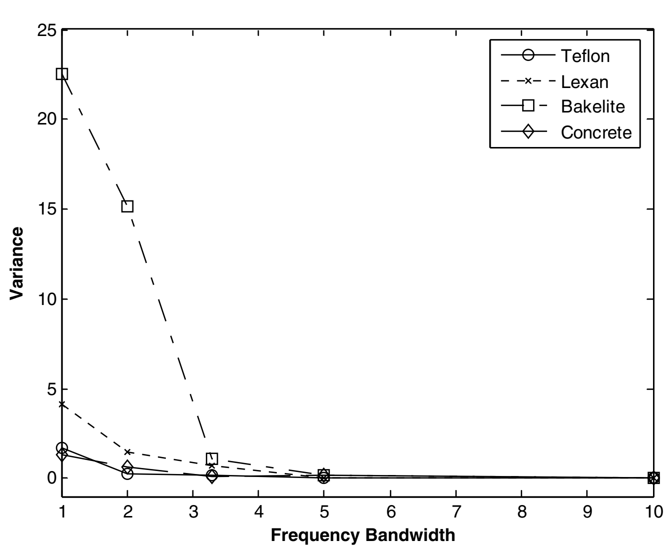

Fig. 6. Convergence of estimates of dielectric constant at difference frequency bandwidths using TDOA.

(2) Accuracy of the use of simplified wave velocity—From EM wave theory it is known that the wave (phase) velocity of EM waves is a function of dielectric properties of materials. For example, for lossy materials, the phase velocity within the medium is [16]

$$v_p = \frac{\omega}{k_R} = \frac{1}{\sqrt{\mu\varepsilon}} \cdot \left[\frac{1}{2}\left(\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}+1\right)\right]^{-1/2}$$

$$\text{(Theoretical } v_p \text{ for lossy materials)} \quad (10)$$

where k_R is the real part of the complex wavenumber, $k = k_R + j \cdot k_I$, and μ is the magnetic permeability (H/m). The first order expansion of v_p provides its approximation as

$$v_p \cong \frac{1}{\sqrt{\mu\varepsilon}} \cdot \left[1 + \frac{1}{8}\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right]^{-1}$$

$$\text{(Approximated } v_p \text{ for lossy materials)} \quad (11)$$

For lossless materials $\sigma = 0$ and the wave velocity becomes

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r'\varepsilon_r'}} \quad (12)$$

where μ_r' is the relative magnetic permeability. For non-magnetic materials such as concrete, v_p becomes $\frac{c}{\sqrt{\varepsilon_r'}}$ which is the wave velocity representation used in the TDOA estimation. Eq. (12) is used in the TDOA procedure described in this paper because of its simplicity, and it is considered as a convenient approximation of Eq. (11) when $\sigma/\omega\varepsilon \ll 1$. To study the accuracy of this approximation, a quantitative study was performed. Wave velocities using Eqs. (10)–(12) are calculated with respect to different values of $\sigma/\omega\varepsilon$ ranging from 0 to 20, shown in Fig. 7. It is observed that the differences between Eqs. (10) and (12) or between Eqs. (11) and (12) may be substantial when $\sigma/\omega\varepsilon$ is greater than 1. In the range of investigation where $\sigma/\omega\varepsilon < 0.1$, the difference between either Eqs. (10) and (12) or Eqs. (11) and (12) is insignificant as demonstrated in Fig. 7(b). Hence, the use of Eq. (12) in our methodology for low-loss materials is justified.

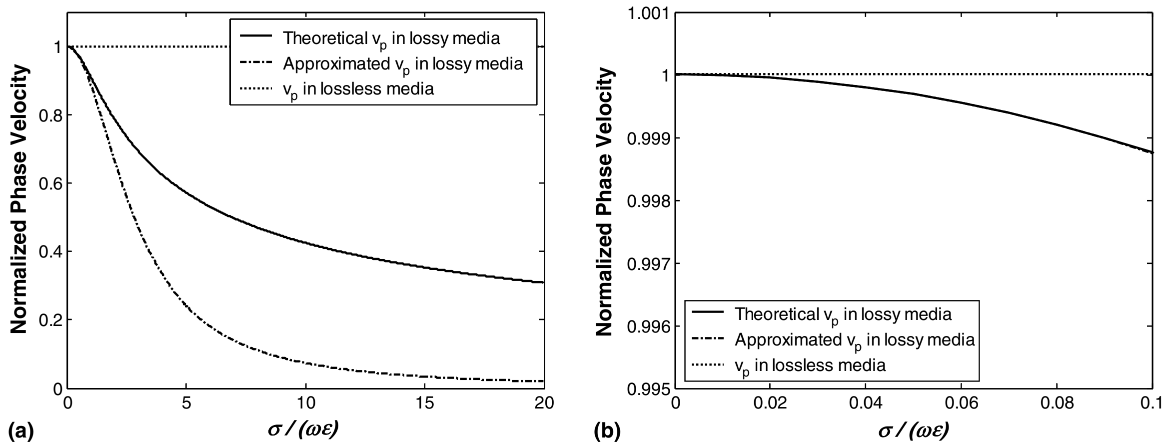

Fig. 7. Normalized phase velocity vs. loss factor: (a) $\sigma/\omega\varepsilon = 0$–20, (b) $\sigma/\omega\varepsilon = 0$–0.1.

5. Conclusion

Non-unique combinations of dielectric constant and loss factor are encountered when lossy materials are measured. In order to resolve this issue, an integrated methodology for determining the unique combination of complex permittivity based on measured transmission coefficient and time difference of arrival (TDOA) information is proposed. The methodology consists of a root-searching procedure based on parametric systems identification and an estimation of the real part of complex permittivity based on TDOA. Studies performed on selected specimens of Teflon, Lexan, Bakelite, and Portland cement concrete show good correlation with previously reported values. One limitation of the proposed method relates to the determination of dielectric constant for very thin specimens such as the GFRP sheet with a thickness of 1.5 mm as used in this study. Our preliminary investigations indicate that the measurement of specimens with a thickness of 6 mm or larger provides satisfactory results. This is not considered to be a significant limitation in measuring properties of construction materials since typical dimensions involved in construction applications are greater than such a thickness. It is anticipated that the proposed methodology will be applicable to the in-situ measurements of dielectric properties in construction applications for effective non-destructive evaluation of materials and structures. The developed method has practical advantage in application to variety of materials. However, the results reported in this paper are preliminary and further validation will be necessary as more measurements become available.

Acknowledgements

The support for this work was partially provided by the National Science Foundation through Grant CMS-0324607, and by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory through Grant ACC-376 (Advanced Concepts Committee). Wide-bandwidth radar measurements were performed at MIT Lincoln Laboratory under the supervision of Dennis Blejer. We gratefully acknowledge his efforts and contributions to the research reported in this paper.

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