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Noniterative complex permittivity retrieval using calibration-independent waveguide measurements

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ABSTRACT

Calibration-independent nonresonant measurements can be employed to eliminate the need for calibration before microwave measurements. These methods generally assume that the location of the sample in its measurement cell is known after the sample is positioned or shifted within the cell and that the length of the measurement cell is known. In addition, in general these methods necessitate some sort of numerical analysis to retrieve the complex permittivity of the sample. In this research paper, we propose a calibration-independent nonresonant waveguide method to first eliminate measurement errors arising from inaccurate knowledge of the location of the sample within its cell (after shifting) and arising from improper knowledge of the length of the measurement cell and second to determine the complex permittivity explicitly. In addition, our proposed method needs scattering parameter measurements from three different measurement configurations – another improvement with respect to a similar calibration-independent method requiring measurements from four different configurations. Furthermore, it does not necessitate that the sample be flushed to the measurement cell. We analyzed repeatability of cell connection and investigated uncertainty in the measurement of complex permittivity for a change in length of the sample and the cell and when air gap present between sample surfaces and guide walls. We validated the proposed method by measuring the complex permittivity of polyethylene sample and distilled water at X-band (8.2–12.4 GHz).

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1. Introduction

The study of materials science is an interdisciplinary theme covering a wide range of applications such as processing and management of materials in agriculture, food engineering, medical treatments, bioengineering, and concrete industry [1–3]. There are already many techniques available in the literature for characterization of materials. These methods can be in general categorized into resonant methods (mono-frequency or narrow-band) and nonresonant methods (broadband) [3]. Many factors such as the frequency range, required measurement accuracy, sample size, state of the material (liquid, solid, powder and so forth), destructiveness and non-destructiveness, presence of contactness (contacting and non-contacting (contactless)), region of field (near-field or far-field), possibility of time-domain or frequency-domain measurements and requirement of calibration (or reference measurements) have to be considered when choosing the appropriate technique to obtain the desired information on properties of the material under investigation. Resonant methods rely on the measurement of a change in resonant frequency and a change in quality factor of the resonating modes in the cavities after the sample is inserted into the cavity (e.g., waveguide cavity) [4–6]. These methods generally assume that the inserted sample into the cavity does not much alter the resonant and quality characteristics of the cavity (low-perturbation approach) [7]. This approach can be extended to electromagnetic characterization of high-loss materials [8]. Generally, frequency-domain measurements are applied for characterization of materials by resonant methods. In a recent study, it has been shown that by measuring the frequency of ringing and the time constant of the exponential decay, which can respectively be associated to the resonant frequency and quality factor of the resonator, it is possible to characterize materials by short-duration signals [9]. Resonant methods are non-invasive and non-destructive in the sense that they do not deform or damage to a prepared sample during and after measurement process. A small fraction of samples (mainly solid samples) to be inserted into the resonant cavity is usually needed for measurements by resonant methods, which is a desired feature for characterization of expensive samples. Because resonant methods rely on near-

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field measurement of wave-matter interaction or coupling of the material under investigation with stimulus wave within a resonant cavity, their accuracy and sensitivity are superior to the accuracy and sensitivity of non-resonant methods. In addition to the aforementioned advantages and features of resonant methods, they have some limitations. First, resonant methods when used to characterize a material within a composite structure require reference measurements (e.g., characterization of thin ferroelectric KTN samples deposited over MgO dielectric substrate requires the reference measurements for quality factor and resonance frequency of the substrate MgO inserted into the cavity [6]). Second, they require a meticulous sample preparation so that any inaccurate knowledge about the volume/dimension of the prepared sample can yield erroneous results [10]. Finally and most importantly, resonant methods are mono-band or narrow-band methods. This circumstance greatly limits the application of resonant methods for electromagnetic characterization of dispersive materials. As an important class of dispersive materials, engineered materials (coined as metamaterials) attracted much attention of scientific community due to their exotic properties such as negative refractive index and thus are used in diverse areas; just to name a few, perfect lens [11], negative-index materials [12] and electromagnetic cloaks [13]. Application of tunable resonators barely increases their frequency band of operation, even with the expense of a decrease in the accuracy.

In addition to different resonant methods, there are a variety of nonresonant methods available in the literature, each having different advantages and disadvantages, to be used for different purposes and applications. Traditional coaxial-line and waveguide methods [14–48], open-ended coaxial-line and waveguide methods [49–56], free-space methods [57–61], and planar structure methods (microstrip line, stripline, and coplanar waveguide) [6,62–65] can be enumerated for nonresonant methods. Among these methods, free-space methods are non-destructive, broadband, and can be applicable for measurements of liquid, solid, and powder materials. In addition, frequency-domain and time-domain measurements can be conducted by free-space measurements [66]. Besides, they are contactless and thus suitable for measurements at high-temperatures [58]. Open-ended coaxial-line and waveguide methods with multiple modes can be utilized for broadband electromagnetic parameter measurements of solid and liquid materials, soft tissues, and composite materials. They are nondestructive and non-invasive methods, and do not usually require much sample preparation. Besides, these methods have the capability of providing near-field, non-contact with lift-off (or contact type), non-invasive, and non-destructive measurements [51]. Coplanar waveguide structures have certain advantages over other planar structures due to the feasibility of fabricating both the conductor and the ground planes over the same surface of the substrate, yielding electric lux lines mainly dominated over the transverse plane of the coplanar waveguides [6]. For this reason, coplanar waveguide structures are mainly used for electromagnetic parameter extraction of materials [6,63–65], as compared with other planar structures. Coplanar waveguide methods are broadband methods and have the convenience of placing the sample under test over the planar structure (non-destructive and non-invasive). Additionally, thin samples can as well be deposited over the coplanar substrate just beneath the coplanar metal strips as another different configuration for accurate measurements [6,63]. They eliminate the problem of traditional coaxial-line methods which require that the sample under test is in the form of torus shape [6].

Due to their relative simplicity, traditional nonresonant waveguide or coaxial-line transmission/reflection methods are presently the most widely used broadband and non-invasive measurement techniques in the literature [16]. In this respect, they can be considered as standard techniques used for evaluating the performance of similar methods as well as new methods proposed for special configurations of samples [6]. These methods make use of the reflected waves by and/or transmitted waves through the sample under test in order to analytically or numerically determine dielectric properties of materials. Although sample preparation for its electromagnetic parameter measurements by the coaxial-line structures is relatively difficult (samples must be prepared in torus form), this drawback is partly eliminated by rectangular waveguide measurements in which samples in rectangular form can be feasibly prepared. Such flexibility of sample preparation for traditional nonresonant waveguide methods allows it to be used for electromagnetic characterization of various forms (solid, liquid and granular) of materials including ferroelectrics [6], vegetation leaves [67], cement-based materials [68], and metamaterials [69].

The aforementioned nonresonant techniques require some sort of calibration before accurate microwave measurements are carried out. Therefore, in the literature various calibration techniques including different number of error terms (8, 12 and 16 error terms) for varied purposes (one-port, two-port, etc.) have been proposed. To name a few, short-open-load-thru (SOLT) [70], thru-reflect-line (TRL) [71], multiline TRL [72], thru-reflect-match (TRM) [73], line-reflect-reflect-match (LRRM) [74], and gated-reflect-line (GRL) [75] can be considered. Accuracy of nonresonant methods can be improved by selection of proper calibration technique considering the requirement of measurement scenario. However, any inaccuracy present in applied imperfect calibration standard(s) in the calibration process can in turn decrease the accuracy of measured electromagnetic parameters by the chosen nonresonant method in the analysis [31,33]. This circumstance can be further problematic if more than one calibration process is required for broadband measurements [72]. Besides, unpredictable (or non-considered) environmental conditions such as different losses and radiation effects [6] can seriously affect the accuracy of calibrated nonresonant measurements. Therefore, there are some approaches needed to eliminate these undesirable drawbacks. Calibration-independent nonresonant methods [30–47], as their name specifies, can be used to achieve this goal. These methods have some definite advantages over calibration-dependent nonresonant methods. First, they eliminate the need for usage of calibration standards, which may not readily be present in all laboratory, to calibrate the measurement instrument (e.g., vector network analyzer, VNA) and can thus improve the measurement accuracy bypassing imperfect calibration standards employed in the calibration process. Second, they can increase the accuracy of measurements by making the measurements resistant to unpredictable and non-considered environmental conditions [76,6] so that the accuracy of calibration-independent non-resonant waveguide methods is partly comparable with the accuracy of resonant methods which are not much affected by the VNA signal to noise ratio [6]. Third, they reduce the overall measurement time without resorting to the application of calibration-standards in the calibration process [43].

In the literature, different sorts of calibration-independent techniques have been proposed for various purposes. While some of them use measurements of raw S-parameters of two samples [32,34–37,33] to extract the complex permittivity (ε_r) of dielectric materials, others utilize raw S-parameters of one sample [30,31,38–46] for the same purpose. In addition, whereas some of them can only be applicable to solid-materials [30–35,40–47], others are useful for liquid samples [36–39]. Calibration-independent methods used to retrieve ε_r of dielectric materials in general require a numerical technique to obtain a solution for ε_r. There are many numerical techniques available in the literature including Newton's method, [77], Muller's method [78], Davidenko's method [79], Cauchy integral method [80], genetic algorithms, sequential quadratic programming, and globalized Nelder–Mead methods

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