JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 17 No 2, 02017(5pp) (2025)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 17 № 2, 02017(5cc) (2025)

OPEN ACCESS

REGULAR ARTICLE

Building Material Complex Permittivity at X-Band Frequencies: An Evaluation

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(Received 15 February 2025; revised manuscript received 20 April 2025; published online 28 April 2025)

A methodology for characterizing dielectric materials frequently utilized in construction is presented. This approach entails assessing electromagnetic wave propagation properties within a waveguide containing the material under investigation, through the analysis of waveguide dimensions, measured parameters, and the implementation of calibration procedures. The method uses the Transmission/Reflection (T/R) technique to ascertain the complicated relative permittivity of various materials. A standard vector network analyzer is initially employed to estimate the S_{ij} parameters within a rectangular waveguide containing the material under investigation in the X-band frequency spectrum (8.5 – 12.5 GHz). Subsequently, a numerical optimization process is applied to derive the complex permittivity, utilizing a MATLAB script designed to identify the complex relative permittivity of the dielectric material, aligning the measured and calculated values of the S-parameters. Specifically, two measures of transmission and reflection are employed: The preliminary measurement is performed using an empty sample holder or a dielectric reference. Conversely, in the second measurement, the sample holder is populated with the substance for characterization. The legitimacy of this approach is evidenced by experimental findings from various dielectric building materials, including Teflon, cellular concrete, and wood, in comparison with alternative ways, hence affirming the efficacy of the proposed strategy.

Keywords: Dielectric materials, Rectangular waveguide, Complex relative permittivity, X-band.

DOI: 10.21272/jnep.17(2).02017 PACS number: 07.05.Tp

1. INTRODUCTION

Comprehending dielectric properties is crucial, particularly when choosing substrates for circuit design or optimizing electromagnetic energy absorption [1, 2]. At present, various techniques are available for evaluating the dielectric characteristics of materials, including free space methods [3], resonant cavity techniques [4], and transmission line or waveguide methods [5]. Each of these strategies possesses distinct advantages and disadvantages. Free space approaches are appropriate for handling large-form materials; however they may demonstrate diminished precision [3]. Resonant approaches provide enhanced accuracy [5]. Waveguide techniques and transmission line methods are widely utilized for accurately measuring the complicated permittivity of materials across a wide frequency range [6]. Waveguide techniques are well-regarded for their precision in evaluating the complicated permittivity of materials. These approaches entail assessing the electromagnetic wave propagation characteristics within a waveguide that encompasses the material being studied. By analyzing waveguide dimensions, and measured parameters, and employing calibration processes, it is possible to estimate the dielectric properties, including complicated permittivity, of the material. This method has broad applicability across various domains, including materials science, microwave engineering, and antenna design [7, 8] [9]. This work introduces a novel method for accurately predicting the complicated permittivity of dielectric materials, motivated by a practical challenge in material selection for construction. The approach focuses on quantifying the S_{ij} parameters of a rectangular waveguide in T/R coupling and utilizing optimization tools in Matlab, particularly the f_{min} search function. The advantage of our technique is in its precision in determining the complex relative permittivity of construction materials. Its

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Cite this article as: M. Bendaoued et al., *J. Nano- Electron. Phys.* 17 No 2, 020017 (2025) https://doi.org/10.21272/jnep.17(2).02017

distinguishing feature is the capacity to characterize materials with-out necessitating the calibration of a vector network analyzer. It depends exclusively on continuous measurements of wave propagation within a rectangular waveguide that contains a material sample, by assessing the propagation constants, including the phase constant and attenuation constant, of the waveguide with the material sample and comparing them to the established propagation constants of the empty wave-guide. This method offers a direct mechanism to ascertain these parameters by measuring the propagation constants of the waveguide both with and without the material sample. This research employs this method to calculate the complex relative permittivity of diverse materials in the X band, highlighting the benefits for substances including wood, cellular concrete, and Teflon.

2. PRINCIPLE OF THE METHOD

To determine the complicated relative permittivity of dielectric materials, the standard technique entails a thorough analysis of the individual scattering parameters (s_{ij}) inside the matrices s_1 and s_2. By comparing these values, useful insights into how variations in lengths (d_1 and d_2 in Fig. 1) may affect the transmission and reflection behaviors of the waveguides can be obtained.

Fig. 1 illustrates the transitions between the measuring cell and the vector network analyzer (VNA) at the planes (port1-Air) and (Air-port2). S_{IJ} parameter measurements during the calibration of Plans X and Y eliminate systematic inaccuracies in the VNA.

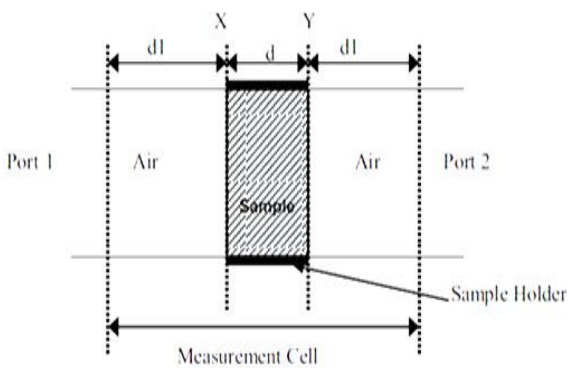


Fig. 1 – Schematic of the measurement cell with the sample of the substance to be characterized

$$\mathrm{S_{1i}} = \begin{bmatrix} \mathrm{S_{11i}} & \mathrm{S_{12i}} \\ \mathrm{S_{21i}} & \mathrm{S_{22i}} \end{bmatrix} \qquad \mathrm{i} = 1{,}2 \tag{1}$$

Using the following equation, the transmission matrices T_1 and T_2 from these two matrices: [9]:

$$\mathrm{M_{1i}} = \frac{1}{\mathrm{S_{21i}}} \begin{bmatrix} \mathrm{S_{12i}S_{21i} - S_{11i}S_{22i}} & \mathrm{S_{11i}} \\ -\mathrm{S_{22i}} & 1 \end{bmatrix} \tag{2}$$

M_{1i} is the measurement when the sample holder is empty (or filled with a standard dielectric), and M_{2i} is the measurement when the sample holder is filled with the material to be characterized. Alternatively, the following five matrices can also be used to create these transmission matrices:

$$\mathrm{M_1 = \ x.T_{ref1}\,.\,T_1\,.\,T_{ref1}^{-1}\,.\,y} \tag{3}$$

The wave reflections caused by the air/sample/air impedance jump at the X and Y planes have a transmission matrix of T_{refi}.

$$\mathrm{T_{refi}} = \begin{pmatrix} 1/1-\Gamma\mathrm{i} & \Gamma\mathrm{i}\,/1-\Gamma\mathrm{i} \\ \Gamma\mathrm{i}\,/1-\Gamma\mathrm{i} & 1/1-\Gamma\mathrm{i} \end{pmatrix}$$

and

$$\Gamma_\mathrm{i} = \frac{\Upsilon_0 - \Upsilon_\mathrm{i}}{\Upsilon_0 + \Upsilon_\mathrm{i}} \qquad (\mu_\mathbf{r}^* = 1)$$

$$\mathrm{M_2 = \ x.T_{ref2}.\,T_2\,.\,T_{ref2}^{-1}.\,y} \tag{4}$$

The matrices x and y include the deviations and anomalies originating from the Vector Network Analyzer (VNA), together with the effects of the inter-connecting cables. We presume that these matrices maintain consistency for each transmission line connected to the VNA. Conversely, Ti represents the transmission matrix for an ideal transmission line, which can be articulated in a certain format:

$$\mathbf{T_i} = \begin{bmatrix} \mathbf{e^{-\gamma d_i}} & 0 \\ 0 & \mathbf{e^{-\gamma d_i}} \end{bmatrix} \qquad \mathbf{i = 1, 2}$$

$$\boldsymbol{\gamma_0 = j2\pi/\lambda 0}\sqrt{1 + \left(\frac{\lambda_0}{\lambda_c}\right)^2} \quad \boldsymbol{\gamma_i = j2\pi/\lambda 0}\sqrt{\boldsymbol{\varepsilon_{ri}^*}\mu_\mathbf{r}^* + \left(\frac{\lambda_0}{\lambda_c}\right)^2}$$

where $\boldsymbol{\gamma_0}$ and $\boldsymbol{\gamma_i}$ are the propagation constants in the vacuum and in the dielectric, respectively, λ_c and λ_0 is the wavelength in open space, and waveguide wavelength break, respectively.

Then, the matrix created by multiplying M_1 and M_2^{-1} is as follows:

$$\mathbf{M_1M_2^{-1} = x.T_{ref1}.T_1.T_{ref1}^{-1}\,.T_{ref2}.\,T_2^{-1}.T_{ref2}^{-1}.x^{-1}} \tag{5}$$

from Eq. (5), $M_1M_2^{-1}$ and $T_{ref1}.T_1.T_{ref1}^{-1}\,.T_{ref2}.\,T_2^{-1}.T_{ref2}^{-1}$ have the same trace [8, 9]:

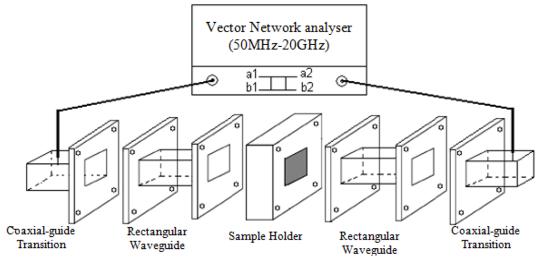
$$\mathbf{Tr(M_1M_2^{-1}) = Tr(T_{ref1}.T_1.T_{ref1}^{-1}\,.T_{ref2}.\,T_2^{-1}.T_{ref2}^{-1})} \tag{6}$$

Or equivalently:

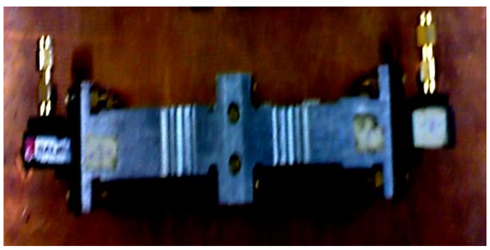
$$\mathbf{Tr\ (M_1M_2^{-1}) = Tr(T_1.T_{ref2}.\,T_2^{-1}.T_{ref2}^{-1})} \tag{7}$$

3. RESULTS AND DISCUSSION

The suggested methodology has been empirically validated by its application to the configuration illustrated in Fig. 2: the measurement apparatus consists of a rectangular waveguide WR90 (sometimes referred to as waveguide size R120) with dimensions of 22.86 mm × 10.16 mm × 10 mm (long). The two 12 cm X-band waveguides on either side filter out higher-order waves. The measurement employs a Vector Network Analyzer (VNA). The VNA is linked to the rectangular waveguide via coaxial transitions, enabling the conversion between TEM mode and TE10 mode and vice versa. The length of these coaxial guidance transitions is 35 mm.



a



b

Fig. 2 – Transmission/reflection measuring device Schematic View (a), photography (b)

The proposed measurement method is first assessed by the X-band dielectric characterization of the vacant cell. Figure 3 illustrates the real and imaginary components of the relative permittivity of Teflon as a function of frequency. Teflon is a widely utilized dielectric material across diverse applications, and this work characterizes its frequency-dependent dielectric characteristics.

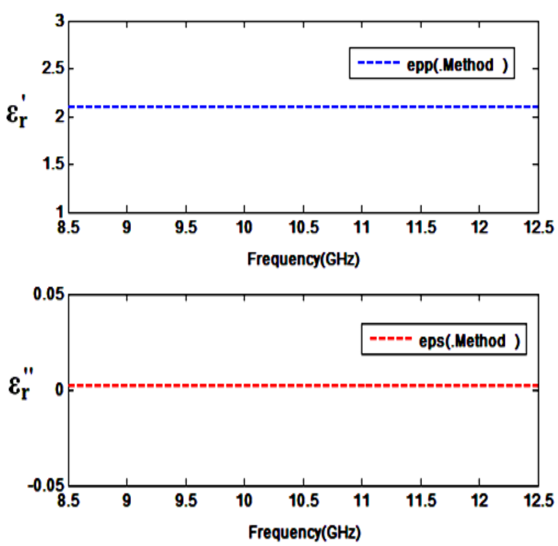


Fig. 3 – Evolution of the complex relative permittivity of Teflon

The report indicates that researchers employed the X band to evaluate the relative permittivity of cellular concrete. Cellular concrete is a composite construction material consisting of sand, air voids, and cement powder. The real and imaginary components of the relative permittivity are illustrated, indicating that cellular concrete functions as a low-loss dielectric material within the X band. The dimensions of the cellular concrete specimen were modified to correspond with those of a rectangular waveguide section in the X band, measuring 22.86×10.16 mm². Measures were implemented to alleviate the impact of the disparity between the conductive walls and the cellular concrete specimen. The observed average relative dielectric permittivity is 1.98, consistent with the current literature on the topic. [10-13].

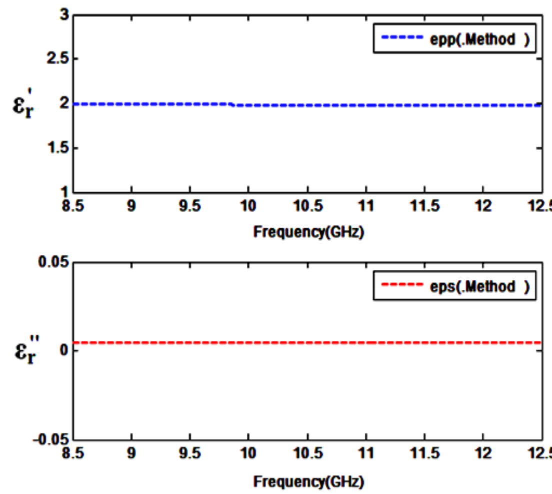


Fig. 4 – Evolution of the complex relative permittivity of Concrete

The validity of the proposed technique was verified by machining an additional wood sample to correspond with the dimensions of the X-band rectangular waveguide section, which measures 1 cm in length. Fig. 5 illustrates the real and imaginary components of the relative permittivity of the wood sample at X-band frequency, demonstrating strong concordance with the findings derived from the iterative Nicholson-Ross approach and mode-matching methods [8, 10, 11, 14].

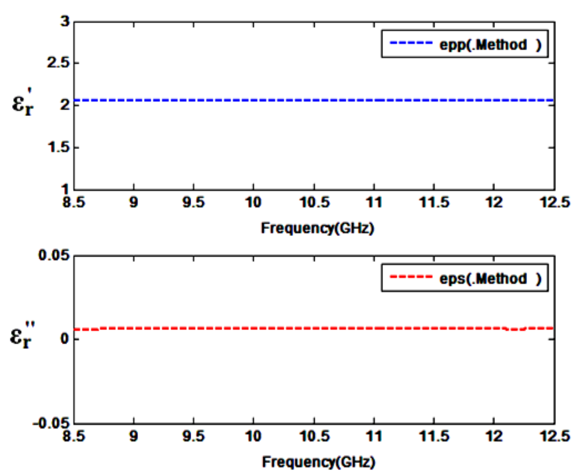


Fig. 5 – Development of complex relative permittivity of wood

Table 1 – The average complex relative permittivity and the average relative error percentage at X-band

Material	$<\varepsilon_r^*>$			<%Error ε_r' >	<%Error ε_r'' >
	Our Method	Measurement (M.M.T)	Measurement (I.N. ROSS)		
Teflon	2.013 – j0.014	2.009 – j0.011	2.012 – j0.016	≤ 0.3	≤ 12
Concrete	2.029 – j0.009	2.034 – j0.006	2.022 – j0.012	≤ 0.8	≤ 11
Wood	2.032 – j0.018	2.021 – j0.021	2.019 – j0.026	≤ 0.6	≤ 8

Table 1 indicates that the inaccuracy in the real component of the complex relative permittivity is minimal (average 0.6%), however the error in the imaginary component may be greater (average < 5 %) for the materials examined. The results demonstrate a strong correlation among the complex relative permittivity's average value for various dielectrics [15]. The estimated complex relative permittivity values using this technique are comparable to those derived by the iterative Nicolson-Ross method and mode matching technique. The results indicate that the technique developed in this study enables the determination of the complex relative permittivity of dielectric materials [15-19].

4. CONCLUSION

This research study presents a novel method for ascertaining the relative permittivity of dielectric construction materials at X-band frequencies. This approach incorporates a rectangular waveguide in-side the X-band spectrum, utilizing an optimization procedure executed via MATLAB. Measurements of S_{ij} characteristics are performed at various frequencies via a vector network analyzer. This method's efficacy in ascertaining the relative permittivity of diverse construction dielectric materials, such as Teflon, cellular concrete, and wood, at X-band frequencies is shown by experimental data and juxta-posed with alternative methodologies in the existing literature.

ACKNOWLEDGEMENTS

The authors would like to thank LMEET-FSTS (Hassan I University) and ERSC/EMI (Mohammed V University).

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Оцінка комплексної діелектричної проникності будівельних матеріалів на частотах X-діапазону

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Представлено методологію дослідження характеристик діелектричних матеріалів, які часто використовуються в будівництві. Цей підхід передбачає оцінку властивостей поширення електромагнітних хвиль у хвилеводі, що містить досліджуваний матеріал, шляхом аналізу розмірів хвилеводу, виміряних параметрів та виконання процедур калібрування. Метод використовує метод пропускання/відбиття (*T*/*R*) для визначення складної відносної діелектричної проникності різних матеріалів. Спочатку використовується стандартний векторний аналізатор мережі для оцінки S_{ij} параметрів у прямокутному хвилеводі, що містить досліджуваний матеріал, у частотному спектрі X-діапазону (8,5–12,5 ГГц). Згодом застосовується процес числової оптимізації для визначення комплексної діелектричної проникності за допомогою скрипта MATLAB, розробленого для визначення комплексної відносної діелектричної проникності діелектричного матеріалу, узгоджуючи виміряні та розраховані значення S-параметрів. Зокрема, використовуються два показники пропускання та відбиття: попереднє вимірювання виконується з використанням порожнього тримача зразка або діелектричного еталону. І навпаки, під час другого вимірювання тримач зразка заповнюється речовиною для характеристики. Легітимність цього підходу підтверджується експериментальними результатами, отриманими з різних діелектричних будівельних матеріалів, включаючи тефлон, ніздрюватий бетон та деревину, у порівнянні з альтернативними способами, що підтверджує ефективність запропонованої стратегії.

Ключові слова: Діелектричні матеріали, Прямокутний хвилевід, Комплексна відносна діелектрична проникність, X-діапазон.