Indoor Material Properties Extraction from Scattering Parameters at Frequencies from 750 GHz to 1.1 THz

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***Abstract*—This paper reports the first ever transmission measurements for a wide choice of different indoor materials such as *wood, plastic, paper, brick, glass* and *leather* at frequencies from 750 GHz to 1.1 THz using up-conversion (frequency-domain) method employing *Swissto12* system. This commercially available system consists of three parts, namely, vector network analyzer (VNA), the material characterization kit (MCK), and two waveguide extenders which measure the *S*-parameters in the frequency range of interest to derive the complex dielectric properties of material samples using stepwise Nicolson-Ross-Weir (NRW) method. These frequency dependent material parameters such as permittivity, refractive index and absorption coefficient are mandatory to analyze and model the wave propagation thoroughly for the aforementioned unexplored frequencies along with the ability to classify and localize these different materials precisely. Until previously, only THz time-domain spectroscopy (THz TDS) system based on down-conversion (time-domain) method is employed to measure the spectroscopic responses for this cause.**

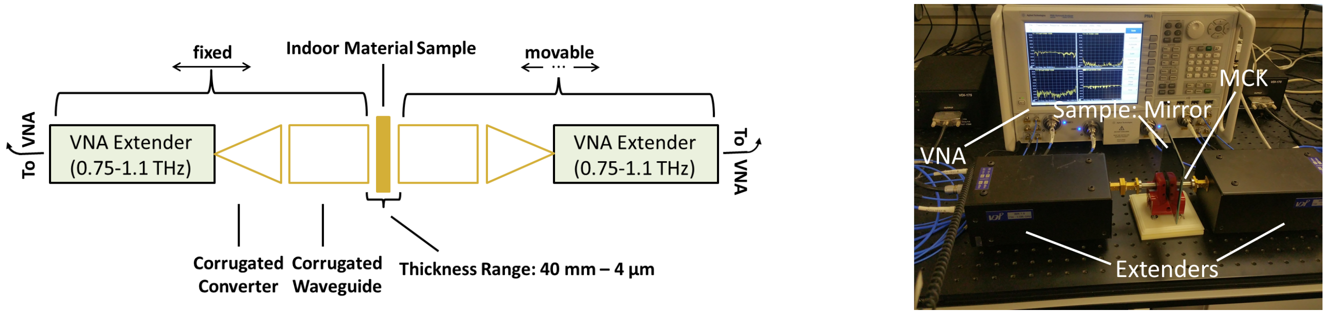
Keywords*—*Terahertz, Terahertz channel modeling, Vector Network Analyzer, Material Characterization.

I. INTRODUCTION

During the last decade, terahertz (THz) frequency region, 0.3-1 THz, has been massively studied and is expected to be one of the possible resources to be exploited for future wireless communication networks beyond 5G. Wireless transmission over this band will offer several advantages such as terabit-per-second (Tbps) channel capacities, and small size transceivers [1]. However, this technology needs to address a couple of challenges in order to reach outstanding performances. In fact, THz application extends to security, medical, biology, aerospace technology, and nondestructive evaluations of materials used in airplanes, such as foams, plastic, and fiberglass composites [2]. Therefore, material dielectric properties' characterization at these frequencies is of paramount importance. It should be accomplished with high precision through appropriate measurement and extraction techniques. While material characterization is extensively investigated at low frequencies, published information is still scares for applications within the THz frequency spectrum region. In fact, the main techniques for characterizing dielectrics are namely, time-domain spectroscopy (frequency down-conversion) and measurements using a vector network analyzer (frequency up-conversion) [3]. The selection of the most suitable measurement method depends on some parameters such as the material phase, temperature and frequency range [4]. In [5] the measured complex dielectric and magnetic properties of liquid and solid biological tissues removed from human arteries at the frequency range from 110 to 170 GHz are presented. The evaluation of the dielectric properties is performed using the Nicholson-Ross-Weir (NRW) conversion process. In [6], an extensive calculation analysis of substrate permittivity, characteristic impedance, total loss, and dielectric loss tangent is presented for up to 500 GHz frequency range. In [7], the characterization of the dielectric properties of a variety of common building and plastic materials between 100 and 1000 GHz using THz TDS transmission system is presented. In fact, the existing reports about dielectric properties of indoor materials are limited, i.e., leather and mirror glass are not characterized yet. Therefore, providing a new database of dielectric properties based on very sophisticated material characterization kit (MCK) already validated in [8] is important. Furthermore, THz Metamaterial samples are characterized in [9]. The presented results are a part of the larger measurement campaign targeting the search of material parameters of a variety of indoor materials between 0.75 and 1.1 THz. Next, this research work is expected to be very useful and helpful for accurate modeling of future indoor wireless communication channels at THz frequencies. In addition, the measured material parameters may also be used for the investigation and development of high-speed wireless networks.

II. STATE-OF-THE-ART

The potential of modern THz systems in material characterization offers a unique solution in imaging, sensing, spectroscopy and communication. Meanwhile, the academia as well as industry are reviewing how this emerging terahertz field might be implemented in a variety of "real world" applications by sharing their experimental database to the world, ranging from the materials' dielectric properties [10], material surface textures [11] and the molecular spectroscopic database [12]. To measure material spectroscopic responses, the state-of-the-art THz systems based on time-domain and frequency-domain methods are classified as follows: (i) THz time-domain spectroscopy (THz TDS) systems [7]; (ii) THz quasi time-domain spectroscopy (THz QTDS) systems [13]; (iii) continuous wave THz (cw THz) systems [14]; and (iv) frequency modulated continuous wave (FMCW) radar transceiver systems [15]. However, each method is confined to specific frequencies, materials and applications in its own constraint. In addition, material characterization kit developed by *Swissto12* is now commercially available (cf. Fig. 1a) which in conjunction



(a) (b)

Fig. 1: Measurement system (a) Schematic diagram of MCK and (b) The 0.75 to 1.1 THz VNA system at University of Glasgow.

with VNAs enables the measurement of both the reflection coefficients (S11, S22) and transmission coefficients (S12, S21) in the WM-250 (or equivalent WR-01) waveguide band that supports frequencies from 750 GHz to 1.1 THz explained briefly later in Section II.B.

A. *Material Samples (Indoor)*

We have characterized six common indoor building materials encountered in the indoor wireless propagation channel. In addition to the channel modeling, the study of propagation (cf. Fig. 2) through different indoor materials can expedite the development of a basic theory for pulse shaping and receiver design. The knowledge of material samples' thicknesses is mandatory in extracting the material parameters and hence, the average of the thicknesses of different indoor materials measured at five different locations is tabulated in Table I.

TABLE I: LIST OF MEASURED MATERIALS WITH THEIR THICKNESS

Material group	ID	Sample	Thickness
Wood	W4	Bamboo (hard wood)	14 mm
Plastic	A3	Vinyl tile sheet	1.2 mm
Paper	P3	Hardboard paper	3.90 mm
Brick	B2	White ceramic wall tile	6.5 mm
Glass	G2	Mirror glass	2.9 mm
Leather	L2	Genuine leather	1.4 mm

B. *Measurement System and Experimental Details*

The experimental system for the THz transmission measurements in this study comprises of three parts, vector network analyzer, the material characterization kit *Swissto12* waveguide system, and two frequency extension modules to measure in the frequency range of 750 GHz to 1.1 THz for different indoor materials. Fig. 1a depicts the schematic layout of the state-of-the-art MCK. A two-port short, open, load, and through (SOLT) WR-01 waveguide standards are acquired to calibrate the measurement equipment. This calibration streamlines the systematic errors between VNA transceivers and waveguide flanges. The MCK kit is made up of two parts and each part further consists of three waveguides, the former one is a rectangular substituted by a circular corrugated one in the middle which finally in the latter most part transits to a low loss corrugated waveguide. The purpose for this transitional waveguide design is to accomplish the THz transmission in an enclosed environment with minimal losses as shown in Fig. 1b. Furthermore, the left hand segment of the setup is fixed as opposed to the movable right one for the ease of characterizing material samples of different thicknesses. As the indoor materials are not chemically pure, we have selected three locations and recorded three readings for each at laboratory temperature 18°C ± 0.2°C with humidity 30% ± 2%.

III. MEASUREMENT TECHNIQUE

In this section, the procedure for processing the measured data and extracting the material parameters is presented.

A. *Stepwise Nicolson-Ross-Weir (NRW) Method*

This work concentrates on measurements of the complex dielectric properties (i.e., permittivity, refractive index, absorption coefficient) of materials extracted from the *S*-parameters' measurements using stepwise NRW method [16]. Besides, this method has been affirmed and documented for the characterization of materials at THz frequencies [17].

B. *Permittivity Extraction*

To derive the complex relative permittivity $\varepsilon_r(\omega)$ from *S*-parameters, the reflection $\Gamma(\omega)$ and transmission coefficient $\mathrm{T}(\omega)$ needs to be obtained first as follows

$$\Gamma(\omega) = K \pm \sqrt{K^2 - 1}\,, \quad K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{1}$$

$$\mathrm{T}(\omega) = \frac{S_{11} + S_{21} - \Gamma(\omega)}{1 - (S_{11} + S_{21})\Gamma(\omega)} \tag{2}$$

where ω is the angular frequency of the THz waves. Note that the reflection coefficient should comply with $|\Gamma(\omega)| \leq 1$ for passive materials at hand. Now, by assuming the material sample thickness d the transmission coefficient considering the wave propagation through the material may written as

$$\mathrm{T}(\omega) = \exp(-\gamma d) = \exp\left(-\frac{j\omega n^*(\omega) d}{c}\right) \tag{3}$$

Here, $c = 1/\sqrt{\varepsilon_0 \mu_0}$. From (3) the complex refractive index $n^*(\omega)$ can be obtained. Finally, from the complex refractive

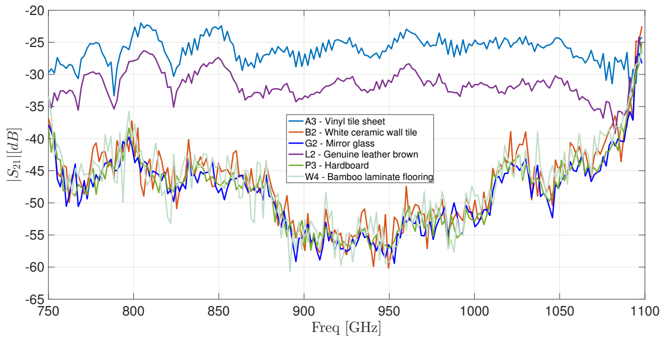


Fig. 2: Measured S-parameter S21 [dB] versus frequency of indoor materials using MCK system.

index one can calculate the relative material parameters such as relative permittivity $\varepsilon_r(\omega)$, relative permeability $\mu_r(\omega)$ [16] and absorption coefficient $\alpha^*(\omega)$ [18].

IV. MEASUREMENT RESULTS

Fig. 3 depicts the measured permittivity as a function of frequency using the stepwise NRW equations. Unlike $\alpha^*(\omega)$ (not shown due to brevity), the permittivities vary inconspicuously with frequency for the materials at hand.

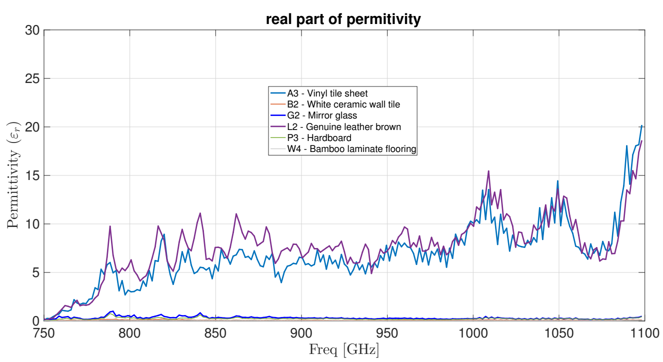


Fig. 3: Measured permittivity response of indoor material samples using the stepwise Nicholson-Ross-Weir (NRW) equations.

V. CONCLUSIONS

Based on the commercially available THz *Swissto12* system, this paper presented material properties (i.e., permittivity) of several indoor materials measured in transmission mode over the frequency range 750 GHz to 1.1 THz. The extraction of the dielectric properties of these materials enable us to study and understand well the wave propagation in this frequency range. Furthermore, the measured data opens the way to advance towards the study of characterizing surface as well as sub-surface materials along with the ability to classify and localize these different materials precisely.

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