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A Method for the Electromagnetic Characterization of Construction Materials Based on Fabry–Pérot Resonance

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ABSTRACT The determination of the complex permittivity of low-loss construction materials at frequency bands above 6 GHz that are being proposed to allocate forthcoming mobile radio services is of critical importance for the design and deployment of future wireless systems. In this paper, a simple free-space method for the electromagnetic characterization of construction materials that does not require multiple reflection or transmission coefficient measurements for different incidence angles or complex optimization procedures is proposed and tested. The method is shown to yield permittivity and conductivity values in agreement with the literature for some common-use materials using a relatively simple measurement setup and procedure.

INDEX TERMS Material characterization, microwave propagation, mm-wave propagation, propagation measurements.

I. INTRODUCTION

A large number of new frequency bands above 6 GHz are being proposed to allocate 5G-and-beyond wireless communication services [1]. The knowledge of the complex permittivity, and therefore of the relative permittivity and of the conductivity of construction materials at such frequencies is critical for the determination of key parameters such as street-corner diffraction or through-wall transmission attenuation, and to properly use deterministic radio propagation prediction tools. Such knowledge is therefore fundamental for the correct design and deployment of future wireless systems.

Several methods for measuring the complex permittivity of materials have been developed over the years [2], [3], each method being suitable for specific frequency ranges, material types and applications. The most popular methods can be classified into four groups:

i. Transmission/reflection line methods [4], [5],
ii. Open ended coaxial probe methods [6],
iii. Resonant methods [7].
iv. Free space methods [8]–[12]

It is worth noting that construction materials are often coarse compound materials (e.g. concrete, asphalt, bricks, etc.) heavily exposed to humidity and temperature changes and showing large variability between different samples, so that an accurate characterization is hardly possible. Rather than accuracy, simplicity, speed of execution and the possibility of performing contact-less, non-destructive measurements of large material samples are important features of a good construction material characterization method. For these reasons free space methods (iv) are the most commonly used methods at radio frequencies. Such methods allow the estimation of average or *effective* electromagnetic parameters of compound materials, which would be difficult or impossible to measure using smaller-scale methods. Potential problems are the presence of unwanted multipath propagation and the need for complex calibration procedures, since the absolute value of the complex reflection and transmission coefficients is commonly measured. Moreover, conventional free-space material characterization approaches usually need multiple measurements for different incidence/reception angles that require rotating positioners, the use of complex maximum-likelihood parameter determination (optimization) methods if not the solution of scattering equations [11], [12].

Since most construction materials are available into slab form (e.g. walls, plasterboard, wooden boards, glass, etc.) we propose a measurement technique based on the

Fabry-Pérot resonance of the material slab [13], a well known phenomenon that's particularly evident when a large enough bandwidth is considered. Instead of performing multiple measurements on a material sample for different incidence/reception angles and applying optimization methods to determine its complex permittivity, we propose to use a wide measurement bandwidth to extract the same information from the difference between adjacent resonance frequencies using a simple, fixed setup. A bandwidth of 1-2 GHz is enough to highlight 2-3 resonance peaks and dips and to apply the method in most cases: over such a bandwidth the complex permittivity of construction materials at frequencies above 6GHz is generally constant [14].

Methods based on a similar background have been proposed in the literature to determine the dielectric constant of microcrystalline liquids and gases or other materials mainly used in optical and electronic devices [15]–[18]. However such methods make use of mirrors to implement a Fabry-Pérot resonator beforehand and to determine material parameters from the changes in the resonance frequencies caused by the material insertion. This would be difficult to implement at radio frequencies over large-scale construction material samples. Therefore, the mirror-less resonance of the material slab itself is used in this work instead.

Unlike other free-space methods based on the measurement of the absolute value of the reflection and transmission coefficients, the slab's frequency response pattern is used here, and therefore the need for calibration using reference material samples – i.e. metal plates - is eliminated. Moreover, the determination of the real part of the permittivity of low-loss materials is virtually decoupled from that of the imaginary part (see section II) and therefore the parameter determination procedure is simpler.

The purpose of the present work is to demonstrate the feasibility of the method and to apply it to some common construction material samples. Further work including application to a larger number of material samples will be needed to assess the actual applicability range and accuracy of the method.

II. THE METHOD BASED ON FABRY-PEROT RESONANCE

If a plane wave impinges on an infinite lossless dielectric slab a resonant phenomenon takes place due to of a series of waves undergoing multiple reflections - and transmissions - within the slab (see Fig. 1).

The effect can be formally described using the Fabry-Pérot interferometer model [13]. Resonant conditions corresponding to minima of slab reflectivity and maxima of transmittivity, occur for:

$$\sin(\delta) = 0 \Longrightarrow \delta = \mathrm{k}\pi \quad \mathrm{k} = 0, 1, 2, \ldots \tag{1}$$

where δ is the phase difference between each successive transmitted path at the medium-air interfaces, which is equal to:

$$\delta = \mathrm{k}_0 \cdot \sqrt{\varepsilon_r} \cdot 2\mathrm{W} \cdot \cos\theta_t \tag{2}$$

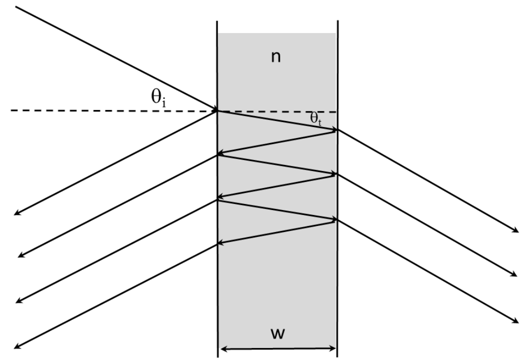

FIGURE 1. Multiple reflections of a plane wave inside a plane infinite slab.

where $k_0 = 2\pi/\lambda_0 = 2\pi\mathrm{f/c}$ is free space's wavenumber, and the rest of the right hand-side term is the excess optical path of each wave bounce, where ε_r is the relative dielectric permittivity of the medium, w is slab width and θ_t is the refraction angle. Using eq. (1), (2) and Snell's law, ε_r can be extracted as a function of the distance between two adjacent resonant frequencies Δf:

$$\varepsilon_\mathrm{r} = \left(\frac{\mathrm{c}}{\Delta\mathrm{f} \cdot 2\mathrm{W}}\right)^2 + \sin\theta_i \tag{3}$$

where c is the speed of light. Therefore by measuring the reflectivity of the slab for a given incidence angle θ_i over a wide enough bandwidth to show at least a couple of resonance notches (see Fig. 2), the frequency-distance between two adjacent notches Δf can be derived and ε_r estimated through (3) with a single measurement shot. Of course Δf must be small enough to assume ε_r constant over it, otherwise the average value of ε_r over the Δf window would be estimated! To this end the slab's thickness w must be large enough to keep Δf low given ε_r, as shown in (3). A thickness of a few centimeters is enough for most materials.

Formula (3) can be used also for low-loss materials, where $\varepsilon_\mathrm{r} = \varepsilon' - j\varepsilon''$ with $\varepsilon'' << \varepsilon'(\varepsilon'' = \sigma/(2\pi\mathrm{f}\varepsilon_0))$ with σ the material's conductivity [S/m]), which include the vast majority of building construction materials. To show this, we make use of the plane-wave series formula of a slab's reflection coefficient derived in [19], which is equivalent to the Fabry-Pérot model but holds true for lossy media. Such a formula is shown below for the case of normal incidence for simplicity:

$$\Gamma(f) = \frac{\Gamma_1(1 - e^{-2j'w})}{1 - \Gamma_1^2 e^{-2j'w}} = \frac{\Gamma_1(1 - e^{-2\alpha' w}e^{-2j\beta' w})}{1 - \Gamma_1^2 e^{-2\alpha' w}e^{-2j\beta' w}} \tag{4}$$

where Γ_1 is the Fresnel's reflection coefficient at the air-medium interface and $k' = \beta' - j\alpha'$ is the propagation constant of the slab material [19]. By expanding the terms in (4) that depend on ε_r (i.e.α', β' and Γ_1) in a Taylor's series under the low-loss assumption and truncating them at first order it is possible to show that the resonance frequencies of (4) do not change with respect to the lossless case.

This is also shown in Fig. 2 where Γ(f) is plotted vs. f for a material with $\varepsilon' = 7$: it is evident that the resonance dips don't appreciably change their position with the conductivity σ, even when σ is equal to 0.15 S/m, i.e. at the limit of the low-loss condition case.

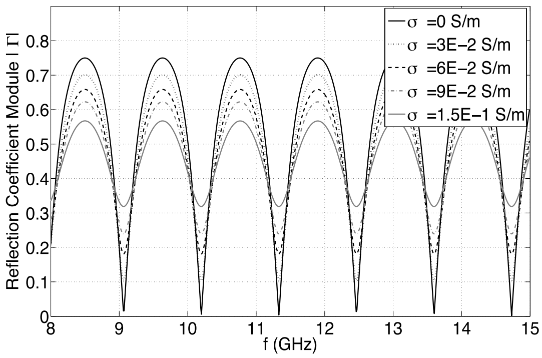

FIGURE 2. $|\Gamma(f)|$ **vs. frequency f for different conductivity values;** $\theta_i = 0°$ **and** $\varepsilon' = 7$.

Therefore, the parameters of low-loss materials can be determined as follows:

a) ε' is estimated using (3)
b) ε' is inserted into formula (4), or the equivalent formula for a generic incidence angle θ_i
c) ε'' (or σ) is determined by optimizing its value in (4) (or in the equivalent formula) for best match between the measured and computed $|\Gamma(f)|$ over the considered bandwidth

Since c) can be difficult due to peaky shape of Γ(f) with narrow reflectivity dips, ε'' can be determined using instead the plane-wave series expression for the transmission coefficient, derived from the corresponding formula in [19] under the assumption that the two media before and after the slab are the same:

$$\tau = \frac{(1 - \Gamma_1^2)e^{-jk'w}}{1 - \Gamma_1^2 e^{-2jk'w}} \quad (5)$$

In the present work (see next section) we actually used the transmission coefficient, measured and simulated through (5) for step c).

Since reflection or transmission coefficients for inhomogeneous materials such as wood often do not show such a clean and regular trend vs. f as shown in Fig. 2, it is necessary to use caution when estimating Δf (step a) or matching the measured and simulated coefficients (step c). Spectral analysis using the Fast Fourier Transform (FFT) on the measured Γ(f) to estimate Δf, while careful visual matching or graphical curve fitting techniques such as least-squares methods can be used for step c). The description of such known techniques is beyond the scope of this work.

III. MEASUREMENT SETUP AND EXAMPLES

Measurements have been performed in a normal room using two vertically polarized, wideband horn antennas with a gain of 15 to 18 dBi connected with an Anritsu 37397D Vector Network Analyzer (VNA). The bandwidth is 8 GHz from 7.5 GHz to 15.5 GHz, to sound some of the frequency bands proposed for next-generation communications, with a frequency step of 5MHz. The antennas have been positioned on their pedestal at a height of 20 cm over the measurement table and at a distance of 30cm from the Material Under Test (MUT) to ensure far field conditions. The antennas' -6dB lobe footprints are always contained within the front surface of the MUT.

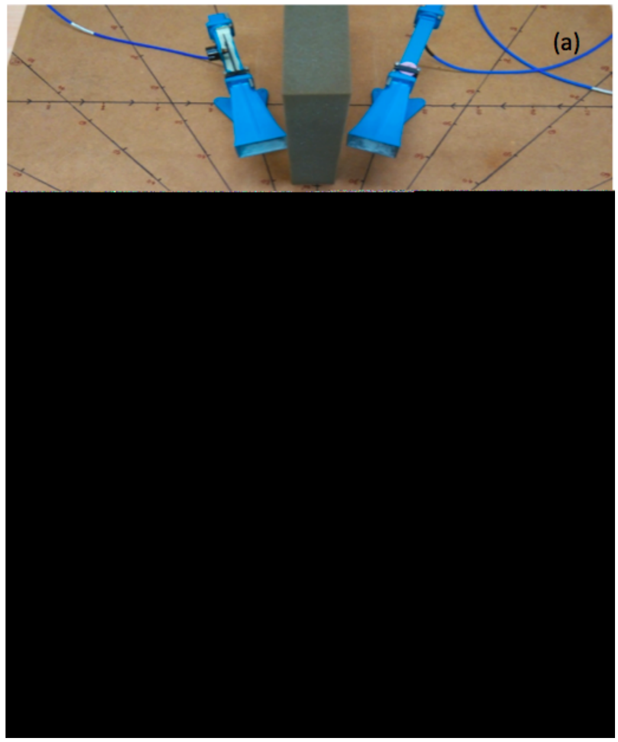

FIGURE 3. Setup for (a) reflection and (b) transmission measurements with antennas, MUT and VNA.

Fig. 3 depicts the measurement set-up. An absorber is used to block the direct path (cross-talk) between the antennas during reflection measurements, which may corrupt results.

Reflection measurements don't need to be calibrated because our goal is not to estimate the actual reflection coefficient value, but only to extract the Δf of the slab's resonance (ref.section II). Transmission measurements must simply be performed by comparing the frequency response with and without the MUT for the same setup in order to estimate the wideband transmission coefficient to be matched using the theoretical coefficient. All measurements are performed easily in one single shot without the need of multiple measurements for different incidence/reception angles that would require rotating positioners. Of course room reflections must be kept low enough to minimize their effects – i.e. spurious multipath fading ripple - on the measurements. The use of an anechoic room might be useful, but is not mandatory: we didn't have problems with our setup in a normal, medium-size lab-room. Measurements appear to be reproducible with very small spread between different measurement sessions on the same sample.

Several MUT slabs have been tested: grey sandstone, yellow-Sahara marble, pine wood, paper stack, medium-density chipboard. All slabs have smooth surfaces, a thickness of 2 to 4 cm and dimensions of at least 60x40 cm, sufficient to minimize border effects.

Measured and best-fit reflected and transmitted power for the grey sandstone slab are shown for example in Fig. 4. Theory and measurements appear to agree very well. Resonant notches are very evident for $|\Gamma(p|$ while the transmission coefficient is less bumpy. Other materials such as pine wood, probably due to the wood's veins and nodes don't show so regular a behavior, but Δf extraction and transmission matching was still possible.

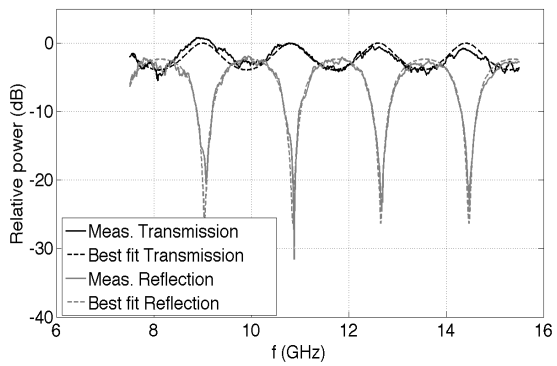

FIGURE 4. Measured and best-fit reflectivity and transmittivity vs. frequency for the grey sandstone slab, $\theta_i = 45°$. Best fit parameters are reported in Table 1.

While ε' is very stable over the considered bandwidth (Δf is constant over the whole bandwidth in Fig 4) ε'' is not as the measured transmittivity appears to be slowly decreasing with f. For this reason we decided to split the bandwidth in two and perform parameters estimation separately for the two sub-bands, as shown in Table I where ε' and σ (S/m) for different materials and for both sub-bands are reported. Results for $\theta_i = 15°$ and $\theta_i = 45°$ are almost the same (as they should) for all cases and therefore we report results for both angles for sandstone, while only results for $\theta_i = 45°$ are shown otherwise.

Estimates derived using frequency-dependent formulas proposed by the International Telecommunication Union (ITU) [14] for the same materials and center-band frequencies are reported in Table I for reference: considering the great variability of construction material characteristics, even for the same kind of material, the agreement is surprisingly good in this case. More generally, values reported in Table I are in good agreement with values reported in the literature for similar materials and frequencies [20]–[22]. Permittivity doesn't change between the two frequency bands considered but does change with the material, while conductivity appears to increase with frequency for all materials except for marble, in agreement with Fig. 4 and with the frequency-dependent formula suggested by ITU [14].

TABLE 1. Estimated ε_r (ε') and σ values. ITU-suggested values are reported in italic for reference where applicable [14].

		7.5-11.5 GHz		11.5-15.5 GHz	
M.U.T.	*Refl.* θ_i	ε_r	σ(S/m)	ε_r	σ(S/m)
Sandstone	15°	7.7	-	7.7	-
	45°	7.7	0.05	7.6	0.09
Marble	45°	6.9	0.15	6.9	0.15
Wood	45°	2.1 *(2.0)*	0.07 *(0.06)*	2.0 *(2.0)*	0.09 *(0.08)*
Chipboard	45°	2.6 *(2.58)*	0.11 *(0.13)*	2.6 *(2.58)*	0.15 *(0.16)*
Paper	45°	2.5	0.115	2.9	0.180

IV. CONCLUSIONS

A method for the determination of the complex permittivity of construction material slabs based on mirror-less Fabry-Perot resonance is proposed. The method only requires a simple fixed measurement setup and the use of a general-purpose Vector Network Analyzer. Moreover the method doesn't require extensive calibration and allows the independent determination of the real and imaginary part of the permittivity. Results are shown to be in agreement with the literature and with ITU formulas.

Further work will have to deal with the application of the method to a larger number of material samples and with the determination of the achievable accuracy of the method with respect to other well-proven methods.

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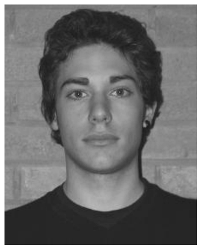

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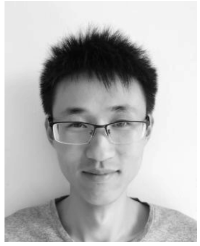

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