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PERMITTIVITY MEASUREMENT AND ANISOTROPY EVALUATION OF DIELECTRIC MATERIALS AT MILLIMETER-WAVES

Carlos A. Fernandes [1], *Jorge R. Costa* [1, 2]

[1] Instituto de Telecomunicações, IST, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal (Carlos.Fernandes@lx.it.pt)
[2] Instituto Superior de Ciências do Trabalho e da Empresa, DCTI, Av. das Forças Armadas, 1649-026 Lisboa, Portugal (Jorge.Costa@lx.it.pt)

Abstract − This paper describes the design and use of an open Fabry-Perot resonator to evaluate the degree of anisotropy of dielectric material samples at millimeter-waves. The proposed implementation not only allows identifying the orientation of the dielectric principal axes but also determining the complex permittivity values along these axes.

Keywords Dielectric permittivity measurements, Anisotropy, Fabry-Perot resonator.

1. INTRODUCTION

Dielectric lens antennas have been successfully used at millimeter- and sub-millimeter wave applications [1]-[4]. Conveniently shaped dielectric lenses can be used to transform the feed radiation pattern into shaped radiation patterns complying with specific templates like high directivity beams [1]-[2], or secant-square shaped beams [3] or even tilted beams for scanning applications [4].

For accurate lens design and accurate prediction of its performance, the lens material complex permittivity value $\varepsilon = \varepsilon_r \left(1 + j \tan\delta\right)$ must be known with at least 1% accuracy at the antenna's operating frequencies. This is especially critical in multiple shell lenses combining different materials [3]. In most cases the electromagnetic characteristic of possible lens materials are specified by the manufacturer for microwave frequencies only, with tolerances that are incompatible with accurate lens design in stringent applications. On the other hand, doubts may arise in some cases about the isotropy of a particular raw material batch. For all these reasons, in-house evaluation of the complex permittivity is required for every new raw material batch before lens design and manufacture when high performance is at stake.

Material isotropy is crucial for common lens designs. In fact, an anisotropic lens material can greatly deform the lens radiation beam shape, so material isotropy must be checked. It happens in some cases that the degree of material anisotropy is too high to obtain a viable lens. But in some cases, if the principal axes associated with the anisotropy are well defined, this can be used instead as an advantage in the lens design to obtain some shaping effects in the radiation pattern that would not be possible with an isotropic material. For instance this could be used to compensate the lack of symmetry of the feed radiation pattern to produce a more symmetrical beam at the lens output. This type of material anisotropy may result for instance from the material fabrication process. For a viable lens design it would be required to determine the orientation of the material principal axes as well as the corresponding complex permittivity values.

2. OPEN RESONATOR

The Fabry-Perot (F-P) open resonator method allows measuring the complex permittivity of dielectric materials at millimeter-waves. Its theory and operation principles for isotropic materials are very well known [5]-[7], and these were used to fabricate one such device (Fig. 1).

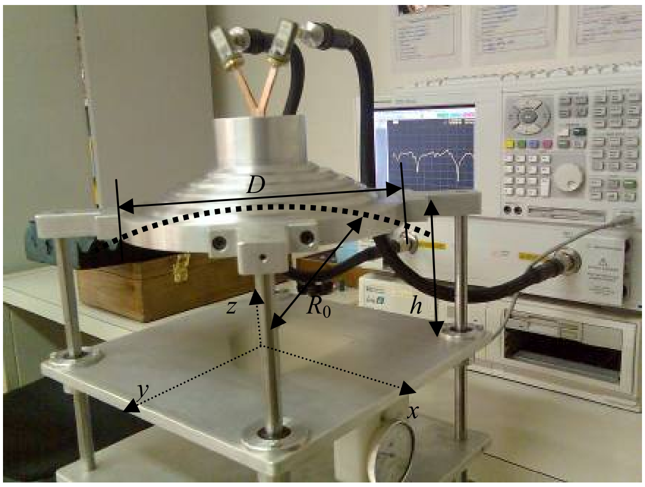

Fig. 1 - Fabricated Farby-Perot open resonator for V-band (40 - 75 GHz) complex permittivity measurements.

A plane-concave configuration was selected for the device, as it involves the fabrication of only one spherical mirror while allowing precise positioning of the dielectric samples directly on the planar mirror without the need for perturbing holders. The spherical mirror is made of Aluminum, with $R_0 = 160.3$ mm curvature radius and $D = 240$ mm projected diameter. A fine linear translation is allowed for the planar mirror along z coordinate; a 10 μm precision gauge is associated with this translation. These dimensions were selected for typical operation within part of the V-band (40 - 75 GHz).

Critical elements of this device, which are scarcely described with enough detail in the literature, are the coupling holes between the waveguides connected to the back of the mirror and the open cavity in front of the mirror. Because of the adopted single spherical mirror configuration, the input and output coupling holes are placed side-by-side near the center of the spherical mirror. The holes diameter, separation and depth are crucial for correct device operation. Different conflicting aspects are involved in its design, including minimization of mutual coupling between holes (which must be typically lower than -80 dB), minimum separation between holes to minimize the excitation of higher order modes in the cavity and appropriate holes depth for maximum power coupling into the open cavity. The design of the coupling holes was done using WIPL-D [8] (Fig. 2). Final dimensions were 0.2 mm, 1.2 mm and 6.8 mm respectively for holes wall thickness, holes diameter and holes separation. Quality factor of the order of $Q_0 = 10^6$ is obtained for the cavity, which is more than enough to measure complex permittivity of the usual low loss dielectric materials. More details are presented in the next section.

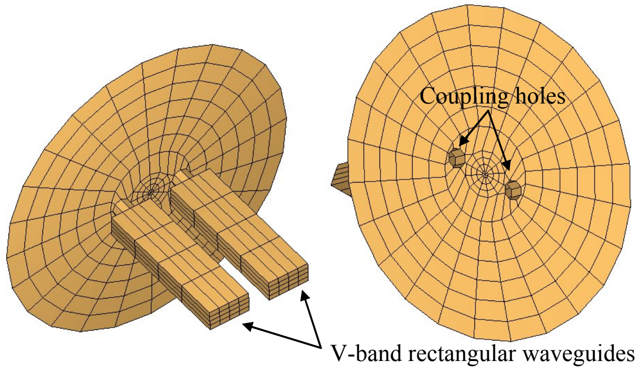

Fig. 2 - Front and back view of a section of the Fabry-Perot spherical reflector model used in WIPL-D for the design of the coupling holes.

Although the system allows for linear translation of the plane mirror as previously referred, it was found more reliable to opt for the fixed distance measurement procedure rather than the alternative fixed frequency method [5]. The central distance between mirrors was fixed to $h = 157.6$ mm. Around 63 GHz, this enables a good compromise between a narrow beam waist of the fundamental Gaussian mode at the planar mirror ($w_0 = 5.7$ mm) and the Gaussian beam width at the spherical mirror ($w_z = 42.9$ mm). It is recommended that the diameter of the sample at the planar mirror is at least 3.4 times larger than w_0 [6]. The above choice makes it possible to measure material samples with diameters as small as 20 mm. Increasing h would in fact reduce w_0 but it would increase w_z with consequent risk of spill over at the edges of the spherical mirror and consequent reduction of the cavity quality factor.

Measurements are performed using a vector network analyzer (Agilent PNA E8361A). Fig. 3a) shows the measured frequency response of the empty cavity s_{12} when using a time averaging factor of 75 to reduce the noise floor. The figure shows five clusters of resonances. These are very sharp with good dynamic range. In each cluster, one of the resonances corresponds to the fundamental Gaussian mode $TEM_{0,0,q}$ and the others to the higher order modes. In order to identify the fundamental mode in each cluster, an absorbing material slab with a centered hole of approximately $4w_0$ is temporarily introduced at the planar mirror. This attenuates all the resonances safe for the fundamental one which has the narrower beam waist, see Fig. 3b).

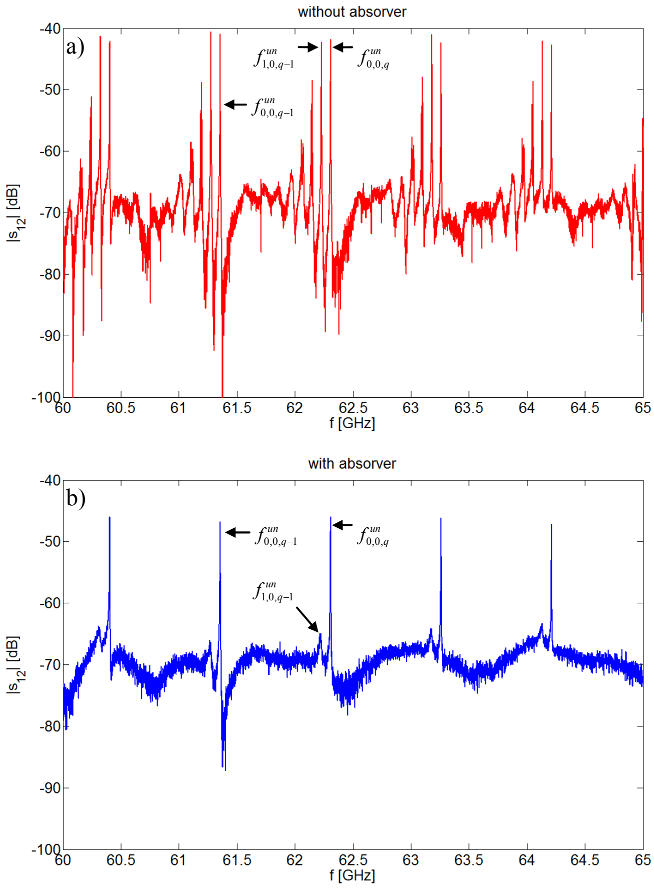

Fig. 3 - Measured s_{12} frequency response of the empty F-P resonator: a) without absorbing plate; b) with absorbing plate

Two consecutive resonances of fundamental modes $TEM_{0,0,q}$ in the empty cavity are used to determine the precise distance between mirrors h [7]

$$h = \frac{2}{c}\left(f^{un}_{0,0,q} - f^{un}_{0,0,q-1}\right). \quad (1)$$

The distance obtained in this way from Fig. 3a) is $h = 157.59$ mm. On the other hand, the resonance frequency of adjacent non fundamental modes $TEM_{1,0,q\text{-}1}$ can be used for precise determination of the curvature radius of the spherical mirror [7]

$$R_0 = h \sin^{-2}\left(\frac{\pi}{2}\frac{f^{un}_{1,0,q-1} - f^{un}_{0,0,q-1}}{f^{un}_{0,0,q} - f^{un}_{0,0,q-1}}\right). \quad (2)$$

The measured curve from Fig. 3a) leads to R_0 = 160.31 mm.

3. PERMITIVITY MEASUREMENT

In order to assess the device, it was used to measure the complex permittivity of polyethylene. Polyethylene is an isotropic dielectric material with low permittivity and low dissipation losses, which is commonly used in the manufacturing of dielectric lens antennas. According to the supplier [9], its permittivity is of the order of ε_r = 2.3-2.4 at 1 MHz. A disk sample of polyethylene (Fig. 4) was cut from a rod with 30 mm diameter. The disk thickness was t = 1.56 mm, which is approximately half the wavelength in the material, as is required by the standard method for best results.

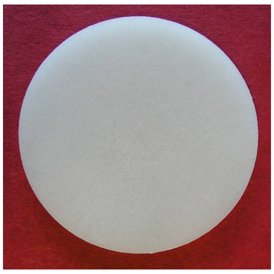

Fig. 4 - Polyethylene sample with t = 1.56 mm thickness.

The extraction of the permittivity follows the standard method [7]. The disk sample of polyethylene is placed at the centre of the plate mirror and the new frequency response of s_{12} is measured. Fig. 5 shows the obtained response from the cavity when loaded with the polyethylene disk.

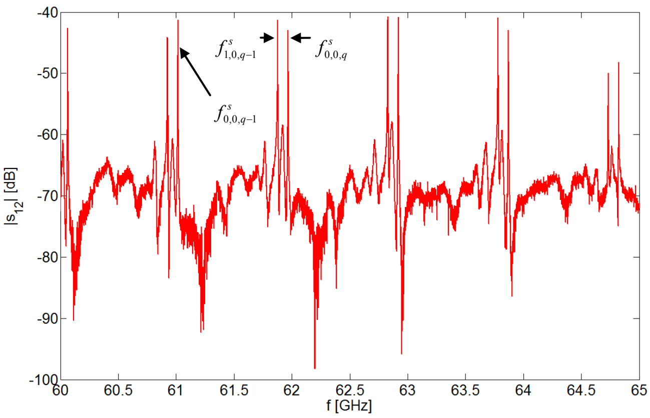

Fig. 5 - Measured s_{12} frequency response of the F-P resonator loaded with the polyethylene sample.

The permititivity value ε_r of the sample can be obtained from the new resonance frequency of a fundamental mode $TEM_{0,0,q}$ by solving the following equation [7]

$$\frac{\tan\left(\sqrt{\varepsilon_r}k_q t-\Phi_t\right)}{\sqrt{\varepsilon_r}}=-\tan\left[k_q\left(h-t\right)-\Phi_d\right], \tag{3}$$

where

$$k_q=\frac{2\pi f^s_{0,0,q}}{c}, \tag{4}$$

$$\Phi_t=\tan^{-1}\left(\frac{t}{\sqrt{\varepsilon_r\left(h+t/\sqrt{\varepsilon_r}\right)\left(R_0-h-t/\sqrt{\varepsilon_r}\right)}}\right), \tag{5}$$

$$\Phi_d=\tan^{-1}\left(\frac{\left(h+t/\sqrt{\varepsilon_r}\right)}{\sqrt{\left(h+t/\sqrt{\varepsilon_r}\right)\left(R_0-h-t/\sqrt{\varepsilon_r}\right)}}\right)-\Phi_t, \tag{6}$$

and c is the speed of light in vacuum.

The loss tangent (tan δ) is determined from the reduction of the empty cavity quality factor value (Q_0) to the dielectric loaded cavity quality factor value (Q_d) [7]

$$\tan\delta=\frac{1}{Q_e}\frac{t\Delta+h-t}{t\Delta+\frac{1}{2k_q}\left\{\sin 2\left[k_q\left(h-t\right)-\Phi_d\right]\right\}}, \tag{7}$$

where

$$\Delta=\frac{\varepsilon_r}{\varepsilon_r\cos^2\left(\sqrt{\varepsilon_r}k_q t-\Phi_t\right)+\sin^2\left(\sqrt{\varepsilon_r}k_q t-\Phi_t\right)}, \tag{8}$$

$$\frac{1}{Q_e}=\frac{1}{Q_d}-\frac{h\left(\Delta+1\right)}{Q_0 2\left(t\Delta+h-t\right)}. \tag{9}$$

Fig. 6 zooms-in Fig. 5 around the frequency of the fundamental mode $TEM_{0,0,q}$. Using the values presented in Fig. 6 and equations (3) through (9), the complex permittivity of the polyethylene was determined with a coverage factor of two as ε_r = 2.349±0.010 and tan δ = (0.386±0.014)×10^{-3}. These values are in agreement with the ones presented in [10] for 60 GHz and validate our implementation of the method. Other tests were performed with different material and the same type of agreement was obtained.

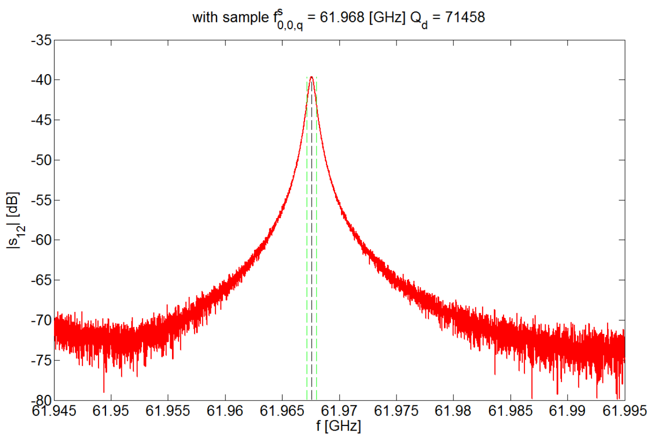

Fig. 6 - Measured s_{12} frequency response of mode $TEM_{0,0,q}$ of the F-P resonator loaded with the polyethylene sample.

4. ANISOTROPY EVALUATION

The F-P resonator was then used to determine the complex permittivity of Shapal-M®. Shapal is a machineable ceramic based on Aluminium Nitride which, according to the manufacture [9], presents high permittivity ε_r=7.3 at 1 MHz. Four disk samples of Shapal (Fig. 7) were cut, two from each edges of a commercially available rod with 20 mm diameter. The disks have a thickness t = 0.86 mm.

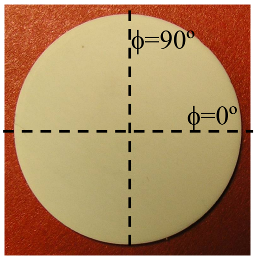

Fig. 7 - Shapal sample with t = 0.86 mm thickness.

As before, the disk samples of Shapal were placed at the centre of the plane mirror and the cavity s_{12} frequency response was measured for each one. Fig. 8 shows the obtained cavity response when loaded with one of the samples.

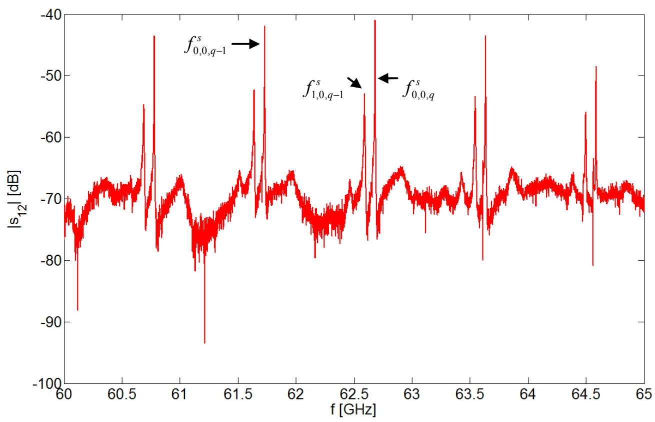

Fig. 8 - Measured s_{12} frequency response of the F-P resonator loaded with Shapal sample with rotation angle ϕ = 0º.

Measurements of the Shapal samples show that the resonance frequencies of the fundamental modes $TEM_{0,0,q}$ actually break-up into two distinct fixed values. Such result can be verified in Fig. 9 that shows a magnification of Fig. 8 around the frequency of the fundamental mode $TEM_{0,0,q\text{-}1}$ for three different rotation angles of the sample. The s_{12} amplitudes at these resonances depend on the rotation angle of the disk sample about the cavity z-axis. When one of the sample principal axes is aligned with the cavity y-axis, only the corresponding resonance appears; this enables to clearly identify the orientation of the sample principal axes and to determine the corresponding complex permittivity values along each axis. For intermediate angles between the two principal axes, s_{12} amplitude is non-zero at both resonances.

The reason why this anisotropy can be clearly discriminated is that the feeding and pick-up rectangular waveguides (Fig. 2) ensure that the Gaussian beams excited in the cavity have a well defined linear polarization. The electrical field in the cavity is mainly polarized along the y-axis (Fig. 1), so the measuring setup allows determining the complex permittivity of a disk sample along its y-axis. In the specific case of the tested rod of Shapal, the material is anisotropic at millimeter waves with two principal axes in the horizontal plane.

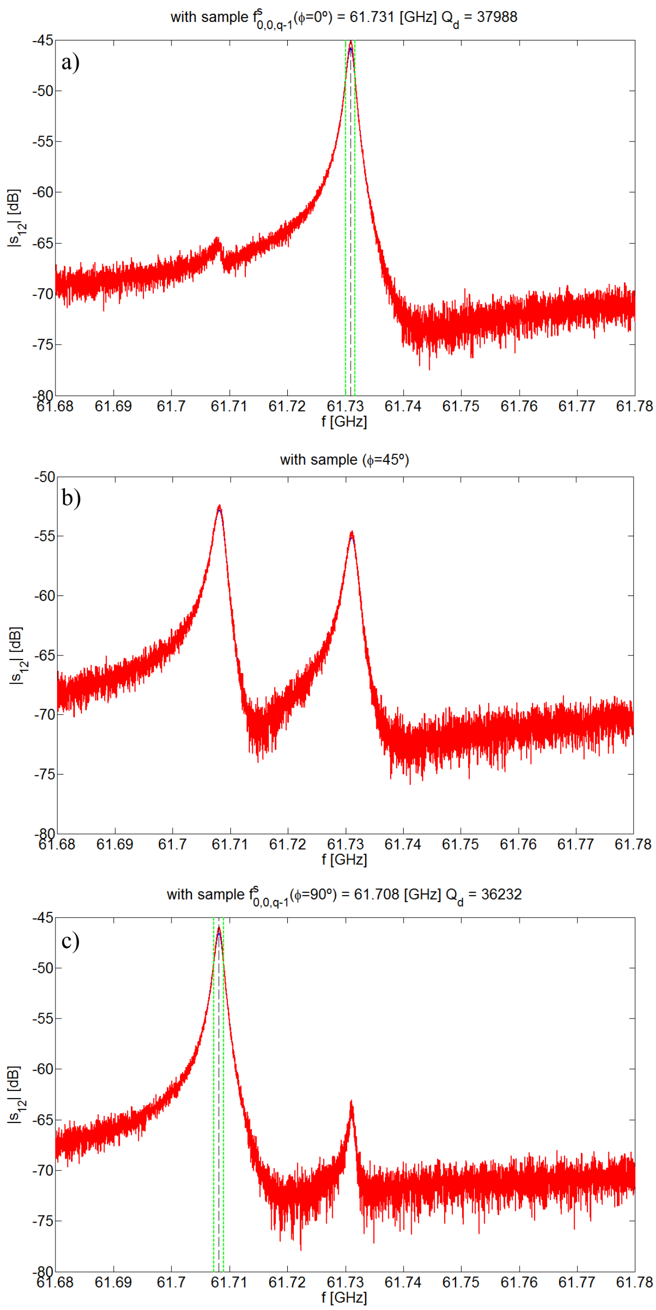

Fig. 9 - Measured s_{12} frequency response of mode $TEM_{0,0,q\text{-}1}$ of the F-P resonator loaded with Shapal sample for different rotation angles of the sample: a) ϕ=0º; b) ϕ=45º; c) ϕ=90º.

The obtained results for the complex permittivity of Shapal are summarized in Table 1 with a coverage factor of two. The obtained values were calculated by averaging 12 measurements corresponding to the permittivity results obtained from 3 resonances in the 60-65 GHz band for each of the 4 Shapal samples.

Table 1 - Measured complex permittivity of Shapal at 60-65 GHz.

ϕ	ε_r	tan δ
0º	6.203 ± 0.054	$(0.166 \pm 0.018) \times 10^{-2}$
90º	7.027 ± 0.061	$(0.147 \pm 0.012) \times 10^{-2}$

4. CONCLUSION

The present paper describes the use of the open resonator measurement procedure as a convenient tool to evaluate the isotropy of dielectric materials at millimeter waves in one plane. The complex permittivity of an anisotropic sample of Shapal-M® has been determined. Disk samples were cut from a Shapal rod and it was possible to evaluate the anisotropy of that particular batch of material and also identify the orientation of the principal axes in the samples.

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