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APPLICATION OF A COAXIAL-FED PATCH TO MICROWAVE NON-DESTRUCTIVE POROSITY MEASUREMENTS IN LOW-LOSS DIELECTRICS

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Abstract—An air-spaced coaxial-fed patch antenna to be used as a microwave sensor for non-destructive porosity measurements in low-loss dielectric materials is presented. The variation of the patch resonant frequency when it is put on the surface of the material under test is used to estimate the dielectric permittivity. Then, a standard two-phase mixture model is used to derive the material degree of porosity from the above permittivity estimate. Measurements at the 2.4 GHz ISM frequency band have been carried out on a set of polymeric samples with artificially induced porosity. The specific choice for the operating frequency is related to the final goal of applying the above microwave sensor for quality control of ceramic materials during the production process.

1. INTRODUCTION

The evaluation of the degree of porosity of polymers and ceramic materials is of great importance in scientific and industrial applications. Indeed, the presence of micro-cavities randomly distributed modifies both the mechanical and electrical properties of the material. Degree of porosity is usually detected by mechanical measurements through a destructive test. First, the weight and the volume of a sample extracted from the material under test are measured and the apparent density is calculated. Then, the sample porosity is obtained by comparison with the density of a reference material sample, i.e., not porous. Alternatively, microwave techniques allow one to perform non-destructive and non-invasive tests, without extracting samples from the material under test, and requiring just one kind of measurement. Microwaves are largely used for material characterization since they easily propagate through low-loss dielectrics and the amplitude of the electromagnetic wave reflected by or transmitted through a material obstacle strongly depends on the dielectric properties of the material itself [1–3]. The most common sensors for microwave non-destructive permittivity measurements are planar antennas, open-end coaxial cables or waveguides. Ultrasounds could be also used, but they require a wave-matching medium (water or gel) to facilitate the wave propagation from the transducer to the sample under test. The above requirement limits the applicability of the ultrasounds during the industrial processes, since the matching medium can alter the characteristics of the material under test. Finally, recent ultrasound transducers that do no need a matching medium are still quite expensive and do not guarantee satisfactory SNR levels.

In this paper, the estimation of the degree of porosity of low-loss dielectric materials through a microwave non-destructive technique (NDT) is carried out by resorting to a simple coaxial-fed patch antenna. The metallic patch has no dielectric substrate (air-spaced patch) and the material under test works as a superstrate layer when the antenna is put onto its surface. By measuring the antenna resonant frequency shift when the material is in tight contact with the metallic patch (with respect to the case of the isolated patch) it is possible to estimate the permittivity of low-loss dielectric materials. Then, by resorting to a standard model that defines the permittivity of a two-component mixture, the sample porosity can be estimated with respect to a reference sample (porosity-free sample). Nevertheless, the proposed microwave sensor can also be used to easily determine relative variations of porosity in different samples of the same material or in different regions of large material samples. A prototype of a coaxial-fed patch antenna operating in the 2.4 GHz ISM (Industrial Scientific and Medical) frequency band has been designed and realized. Measurement results on a set of polymeric samples with artificially induced porosity are shown. Porosity measurements obtained with this sensor differ less than 13.5% from the results obtained by measuring the apparent densities of the samples. The influence of the sample thickness is also discussed.

The paper is organized as follows. In Section 2, a known relationship between the degree of porosity and the permittivity of a low-loss dielectric material is briefly recalled. The main contribution of this paper is given in Section 3, where the design of a microwave sensor for porosity measurements at 2.4 GHz is outlined, and in Section 4, where a quite extensive experimental activity has been carried out to determine the sensitivity, accuracy and limits of the proposed non-destructive measurement technique. Concluding remarks are given in Section 5.

2. PERMITTIVITY VARIATIONS INDUCED BY POROSITY

Porosity arises from the presence of voids randomly distributed through the material. The intrinsic density of a material, ρ_m, is given by the ratio between the mass, m, and the volume, V, of a material sample. If a volume fraction ν, with $0 \leq \nu \leq 1$, is substituted with air, the apparent density, D, is given by:

$$D = (1-\nu)\rho_m + \nu\rho_{\text{air}} = \rho_m + \nu\Delta, \;\text{ with } \Delta = (\rho_{\text{air}} - \rho_m)\,. \qquad (1)$$

Since the porosity of a sample, η, is defined as the volume fraction corresponding to the voids in the material sample, it follows that $\eta \equiv v$. When $\rho_m \gg \rho_{\text{air}}$, from Eq. (1) it results that the porosity can be calculated once the ratio between the apparent density of the sample and the intrinsic density of the material (that one corresponding to a 0% porosity level) are known:

$$\eta \cong (\rho_m - D)/\rho_m = 1 - D/\rho_m \qquad (2)$$

The porosity modifies the electric permittivity of a dielectric material and a simple approximate relationship between the two physical parameters has been derived in [4, 5] by considering a two-component mixture. In particular, the relative permittivity ε of a two-component mixture composed of a volume fraction $(1-\nu)$ with relative permittivity ε_m and a volume fraction ν with unit permittivity (relative permittivity of air) can be approximated by the following mixture formula:

$$\varepsilon^\alpha = (1-\nu)\varepsilon_m^\alpha + \nu, \qquad (3)$$

where the model degree, α, varies between 0 and 1. The model defined in Eq. (3) is valid under the assumption that a sample with thickness t is composed of alternated thin layers, or inclusions, with different dielectric constants; if an electromagnetic wave propagates through a sample whose layers are thin compared with the wavelength λ, the sample can be considered as composed of one slab with thickness t_1 and another one with thickness t_2, with $t_1 + t_2 = t$ [4, 5]. The value of the parameter α depends on both the polarizability of the mixture components and the external electric field. Usually, the parameter α is determined in an empirical way, and its best value depends on each specific application.

A simple expression for the porosity can be derived from Eq. (3), once the permittivity of the sample itself and the intrinsic permittivity of the material are known:

$$\eta = \nu = \frac{\varepsilon_m^\alpha - \varepsilon^\alpha}{\varepsilon_m^\alpha - 1} \tag{4}$$

In a microwave-based NDT the permittivity is usually measured through planar resonant sensors or antennas whose characteristics are significantly modified by a material sample put close to the device [6–8].

3. THE PERMITTIVITY SENSOR

Microwave patch antennas have been often used as permittivity sensors in NDT context. In this section, an air-spaced coaxial-fed square patch antenna operating in the ISM 2.4 GHz frequency band has been designed, realized, and then used to get experimental results. It is worth noting that the same sensor could be designed to make measurements at different frequencies. However, it should be considered that at lower frequencies the size of the patch increases and larger material samples with a relatively flat surface are needed. On the other hand, at higher frequencies mechanical tolerances become more important and more accurate mixture models are needed since the size of the voids may approach the radiation wavelength. In this work, the ISM frequency has been chosen, which is suitable for the quality control of ceramic materials during the production process.

The square patch antenna is shown in Fig. 1. It has been optimized by using the electromagnetic CAD MWS-CST [9]. In order to achieve a satisfactory sensitivity level, the $L \times W$ brass patch (with $L = W = 55\,\text{mm}$) has not been printed on a material substrate (air-spaced patch, $\varepsilon_{\text{sub}} = 1$). Indeed, a similar coaxial-fed square patch antenna printed on a dielectric laminate ($\varepsilon_r \cong 2.35$ and thickness equal to 1.6 mm) has shown a sensitivity factor less than 30% of that one given by the air-filled patch.

The 50 Ω input impedance patch resonates at 2.31 GHz when it is not put on the surface of the material under test (unloaded condition). The patch is set at a fixed distance $h = 5\,\text{mm}$ from the $80 \times 80\,\text{mm}^2$ ground plane by means of a small low-permittivity cylindrical dielectric support (see Fig. 1). In order to obtain a rigid structure, both

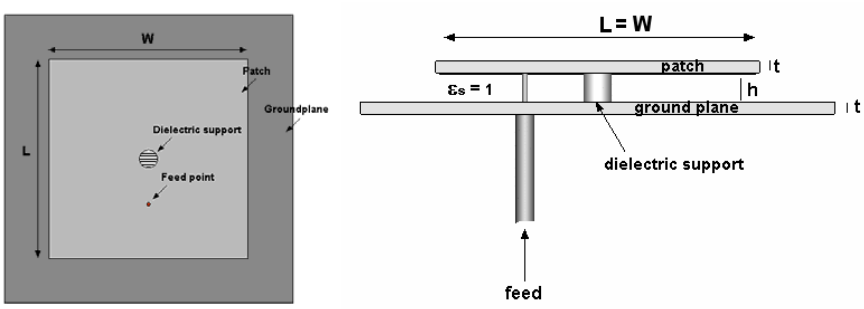

Figure 1. Layout of the coaxial-fed square patch (upper and lateral views). $L = W = 55\,\mathrm{mm}$, $t = 2\,\mathrm{mm}$, $h = 5\,\mathrm{mm}$.

the patch and the ground plane are realized with a thick brass foil (thickness $t = 2\,\mathrm{mm}$). While the size of the patch is imposed by the required unloaded-sensor resonant frequency, the air gap thickness and the position of the feeding point have been chosen to guarantee a return loss less than $-10\,\mathrm{dB}$ whenever the relative permittivity of the homogeneous material filling the half-space above the patch is less than 4. The latter condition ensures a good performance of porosity measurements for materials with an intrinsic permittivity of the material under test less than 4. The resonant frequency of the patch antenna can be calculated by the following approximate expression:

$$f_r = \frac{A}{\sqrt{\varepsilon_{eq}}}, \tag{5}$$

where A is a constant value depending on the antenna geometrical parameters; ε_{eq} is the effective relative permittivity depending on the relative permittivity of the material slab between the patch and the ground plane ($\varepsilon_{\mathrm{sub}}$) as well as on the permittivity of the homogeneous material filling the half-space above the patch (superstrate relative permittivity, $\varepsilon_{\mathrm{sup}}$). When $W/h \gg 1$ and the metal layer thickness cannot be neglected, the effective permittivity can be calculated as suggested in [10–12]:

$$\varepsilon_{eq} = \frac{\varepsilon_{\mathrm{sub}} + \varepsilon_{\mathrm{sup}}}{2} + \frac{\varepsilon_{\mathrm{sub}} - \varepsilon_{\mathrm{sup}}}{2} \cdot \frac{1}{\sqrt{1 + 12h/W}} - \frac{\varepsilon_{\mathrm{sub}} - 1}{4.6} \cdot \frac{t/h}{\sqrt{W/h}} \tag{6}$$

By substituting the last equation into Eq. (5), a simple expression for the resonant frequency is derived:

$$f_r = f_0/\sqrt{a + b\varepsilon_{\text{sup}}}, \tag{7}$$

where f_0 is the resonant frequency of the unloaded antenna ($\varepsilon_{\text{sup}} = 1$), $a+b = 1$ and $b = 0.5\left(1 - 1/\sqrt{1 + 12h/W}\right)/\varepsilon^0_{eq}$, with $\varepsilon^0_{eq} = \varepsilon_{eq}(\varepsilon_{\text{sup}} = 1)$. By inverting Eq. (7), it results that:

$$\varepsilon_{\text{sup}} = \frac{1}{b}\left[\left(\frac{f_0}{f_r}\right)^2 - a\right] \tag{8}$$

To measure the porosity of a material sample, the resonant frequency obtained by positioning the patch on the material sample, f, is compared with that one obtained by posing the patch above a sample of the intrinsic material, f_m. By Eq. (8) it results that:

$$\varepsilon = \frac{1}{b}\left[\left(\frac{f_0}{f}\right)^2 - a\right] \tag{9}$$

and

$$\varepsilon_m = \frac{1}{b}\left[\left(\frac{f_0}{f_m}\right)^2 - a\right] \tag{10}$$

By inserting the above values into Eq. (4) the degree of porosity η of the sample material can be calculated. For the realized patch antenna $f_0 = 2.316\,\text{GHz}$, $a = 0.822$ and $b = 1 - a = 0.178$.

4. EXPERIMENTAL RESULTS

To evaluate the accuracy of the microwave sensor described in Sect. 3, five material samples with different degree of porosity have been prepared by using different percentages of epoxy resin and glass hollow micro spheres (their size is much smaller than the free-space wavelength at 2.4 GHz). For each sample, a mould with a volume $V \cong 120 \times 120 \times 20\,\text{mm}^3$ was filled with a fraction volume, ν, of micro spheres and with the remaining fraction volume, $1 - \nu$, of resin. After solidification, the volume V and the mass m of each sample were measured, and the apparent density, D, and porosity, η, have been calculated. Table 1 shows the results of the mechanical measurements on the samples. The realized square patch antenna has been connected to a Vector Network Analyser HP 8753B, to measure the antenna

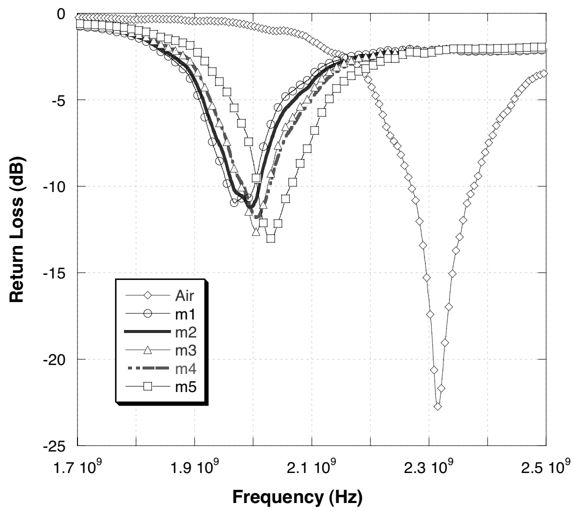

Figure 2. Measured Return Loss of the patch, both in air (unloaded condition) and when it is positioned on the surface of the resin samples with different porosity level (see data in Table 1).

return loss (RL) as a function of the frequency. Fig. 2 shows the measured RL when the sensor is put on the surface of the material samples. The resonant frequency, f_r, is assumed to be the central frequency of the frequency range where the RL is no more then 3 dB above its minimum value. For each sample, the resonant frequency, the permittivity obtained by using Eqs. (9)–(10) and the porosity calculated through Eq. (4) for different values of the parameter α ($\alpha = 1/3,\ 1/2,\ 1$) are listed in Table 2. For each sample, the porosity levels obtained by using three different values of α differ among them less than 6%.

Fig. 3 shows the actual porosity values given in Table 1 versus those calculated through the proposed microwave sensor. Finally, Table 3 shows the results of the linear regression between the actual material porosity and that one calculated with different values of the parameter α. The values of the correlation coefficients show a good accordance between microwave and mechanical porosity estimations, almost for all the values considered for the model degree α. However, by looking at the regression coefficients and intercepts given in Table 3, it results that the choice $\alpha = 1$ gives the best approximation; in this case the mean value of the relative error $\Delta\eta/\eta$ is less than 13.5%. The precision previously stated can be achieved if the sample under test has a flat surface that can be positioned in a strict contact with the sensor.

Table 1. Measured and calculated data of five epoxy resin samples with inclusion of void micro spheres. V = sample volume, m = sample mass, $D = m/V$ = apparent density, η = material porosity (by Eq. (2)).

Sample	V (cm^3)	m (g)	D (g/cm^3)	$\eta_{\%}$
m_1	244.3	285.9	1.17	0.0
m_2	250.0	282.9	1.13	3.4
m_3	248.2	266.6	1.073	8.3
m_4	228.6	243.5	1.065	9.0
m_5	219.9	196.9	0.895	23.5

Table 2. Results of the measurements obtained by inspecting the five resin samples (see Table 1) with the microwave patch sensor. f = resonant frequency, ε = calculated relative permittivity (Eqs. (9)–(10), η = porosity calculated for different values of the model degree, $\alpha = 1/3,\ 1/2,\ 1$, and considering that for the intrinsic material $\varepsilon_m = 3.087$. For comparison purposes, the actual porosity of the sample is reported in the last column.

Sample	f(GHz)	ε	η% ($\alpha = 1/3$)	η% ($\alpha = 1/2$)	η% ($\alpha = 1$)	η% (actual porosity)
m_1	1.975	3.087	0.0	0.0	0.0	0.0
m_2	1.986	3.008	2.8	3.0	3.8	3.4
m_3	2.002	2.888	7.0	7.6	9.5	8.3
m_4	2.004	2.855	7.8	8.4	10.5	9.0
m_5	2.034	2.649	15.9	17.1	21.0	23.5

An air gap between the sample and the sensor, which is unavoidable in case of rough or curved surface, moves the resonant frequency toward higher values and consequently gives higher values of the estimated porosity level. It is worth noting that the size of the square samples has been chosen around a free-space wavelength (12.5 cm @ 2.4 GHz) as we verified that the resonant frequency variations are less than 1 MHz if the distance between the patch border and the sample edge is greater than a quarter of wavelength. The above test has been performed by using samples of the intrinsic material (0% porosity) with different size,

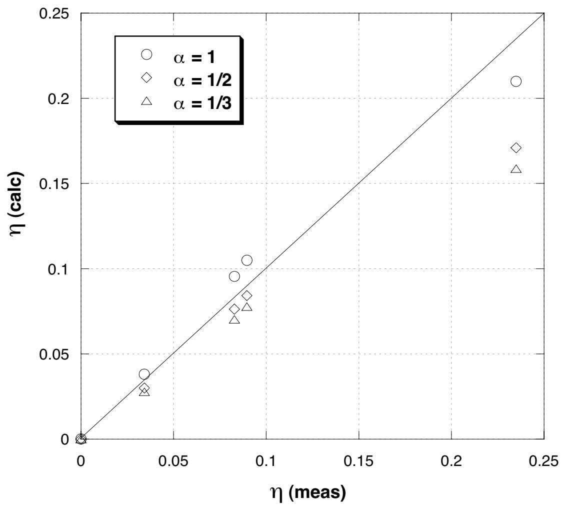

Figure 3. Porosity values, η, calculated with $\alpha = 1/3$, $1/2$, 1, as a function of porosity values derived through the measurements of the sample mass and volume (see η% in Table 1 and linear regression parameters in Table 3).

Table 3. Results of the linear regression of porosity estimates, obtained for $\alpha = 1/3$, $1/2$, 1, as a function of the actual material porosity calculated by means of Eq. (2).

α	**Regression Coefficient**	**Y Intercept**	**Adjusted R-Squared**	**Correlation Coefficient**
1/3	0.666	0.008	0.977	0.991
1/2	0.717	0.009	0.976	0.991
1	0.879	0.012	0.972	0.990

as it represents the test case more sensitive to edge effects.

From Eq. (4), it comes out that if $\alpha = 1$ the porosity of the inspected sample can be obtained by the measured resonant frequency through the following relation:

$$\eta = \frac{\varepsilon_m - \varepsilon}{\varepsilon_m - 1} = \frac{1}{1 - (f_m/f_0)^2}\left(1 - \frac{(f_m/f_0)^2}{(f/f_0)^2}\right) \tag{11}$$

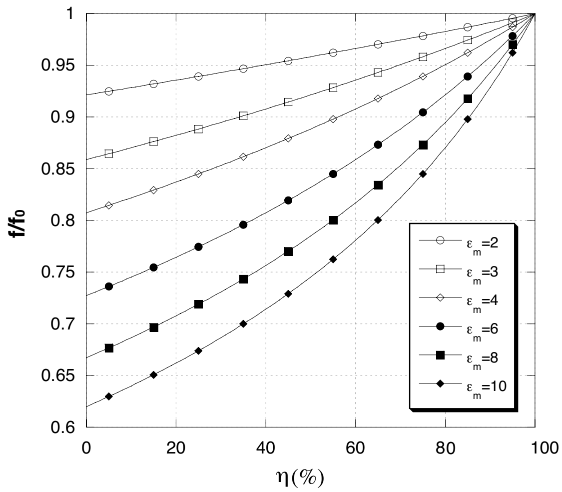

Figure 4. Resonant frequency of the patch sensor normalized to the resonant frequency of the unloaded patch, versus the porosity degree of the material under test and for different values of the relative permittivity of the intrinsic material (porosity free). The curves have been obtained by implementing Eq. (11).

Figure 4 shows the calculated values of the normalized resonant frequency f/f_0 as a function of the percentage porosity, according to Eq. (11). A set of curves relevant to different values of the intrinsic relative permittivity is shown. It can be seen that the resonant frequency depends almost linearly on the material porosity for low values of the intrinsic relative permittivity, ε_m. The mean theoretical sensitivity $S(\eta)$ is given by $S(\eta) = \Delta f/\Delta\eta$, where Δf is the range of measured frequencies in the interval $\Delta\eta \in [0 \div 100\%]$. If $\varepsilon_m \cong 3$ it results that $S(\eta) \cong 3.3\,\text{MHz}/\eta\%$. The effective sensitivity can be evaluated by considering the resonant frequency shift (see Table 2) due to the variations of the porosity η (see Table 1). The resulting mean sensitivity is $S(\eta) \cong 2.5\,\text{MHz}/\eta\%$, in the range $\Delta\eta \in [0 \div 23.5\%]$. Consequently, it results that porosity variations of about 0.5% can be detected with 1 MHz frequency resolution.

Some remarks are needed about the influence of the material finite thickness on the accuracy of the estimated degree of porosity. To analyze the dependence of the resonant frequency on the thickness of the superstrate layer, some simulation results are shown in Fig. 5, when two different materials are considered: Plexiglass and Teflon, with $\varepsilon_m = 2.6$ and $\varepsilon_m = 2.1$, respectively. In the same figure some experimental results are also shown for a number of values of the superstrate thickness (10 mm, 20 mm and 50 mm). It is apparent that the resonant frequency differs less than 5% from the limiting value corresponding to an infinite thickness, if the sample thickness is greater than 20 mm and as long as the relative intrinsic permittivity of the dielectric is greater than 2. As a consequence, Eqs. (8)–(10) that are valid under the hypothesis of an infinite thickness, can be assumed to be valid within a 5% approximation if the thickness of the material samples is greater then 20 mm. As a matter of fact, the permittivity obtained for the sample free of porosity (m_1 in Table 1) differs of only 0.1% from the tabulated value of epoxy resin at 3 GHz: $\varepsilon_m = 3.09$ [11].

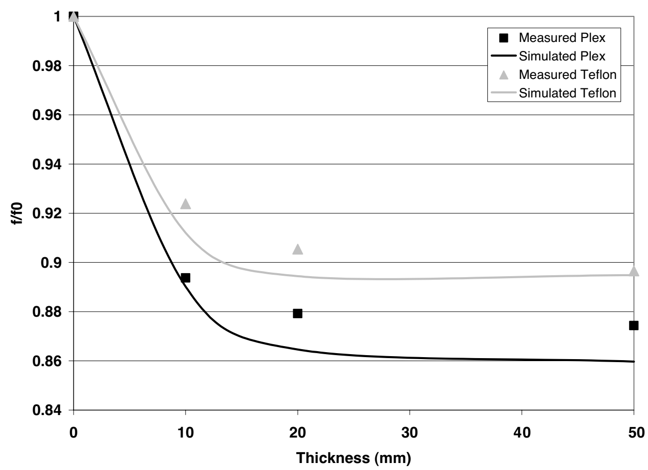

Figure 5. Resonant frequency of the patch sensor normalized to the resonant frequency of the unloaded patch, versus the thickness of the material used as a superstrate layer, when the latter has a relative permittivity $\varepsilon_m = 2.1$ (Teflon) or $\varepsilon_m = 2.6$ (Plexiglass). Simulation results obtained with CST Microwave Studio (continuous lines) are compared with experimental results (markers).

For comparison purposes with the results shown in [13], the dependence of the sensor sensitivity on the degree of porosity has been analyzed by using the experimental results shown in Table 2. The following sensitivity factor has been calculated, as suggested in [13]:

$$SF(\eta) = (\Delta f/f)/(\Delta D/D). \tag{12}$$

From the numerical results shown in Table 4, it is apparent that the sensitivity factor SF in (12) increases as the apparent density increases, i.e., when porosity decreases. This is in agreement with the results obtained by Bramanti in [13], where it has been shown that resonance based methods are more suitable for low porosity materials, with respect to reflection based methods. In [13], the used resonator sensor was an open-end quarter-wavelength coaxial cable, short circuited at the other end and set at a certain distance from the sample surface (contactless sensor). By the way, in [13] the porous material was modelled with a two-phase mixture model such as that in Eq. (3), with $\alpha = 1$.

Table 4. Calculated values of the sensitivity factor, SF in Eq. (11), for the experimental results listed in Table 2. f = resonant frequency, D = apparent density, η = actual porosity of the material samples.

Sample	f (GHz)	D (g/cm^3)	η% (actual porosity)	SF
m_1	1.975	1.17	0.0	-
m_2	1.986	1.13	3.4	$SF_{23} = 0.16$
m_3	2.002	1.073	8.3	$SF_{34} = 0.134$
m_4	2.004	1.065	9.0	$SF_{45} = 0.094$
m_5	2.034	0.895	23.5	-

5. CONCLUSIONS

A coaxial-fed patch suitable for non-destructive porosity measurements in low-loss dielectric materials has been designed. The inspection procedure is quite simple since it just requires to place the sensor in contact with the material under test, without preliminary treatments. By an experimental investigation, it has been shown that the proposed sensor can detect the porosity in a material sample having an area greater or equal to that of the patch and a thickness greater than 20 mm. The estimated porosity is in good agreement with that obtained by the conventional mechanical measurements, and a mean percent error less than 13.5% has been experienced.

The proposed patch-based non-destructive microwave technique is a useful tool in quality control operations, since it can detect with sufficient precision relative porosity variations both in different regions of the same inspected sample as well as between different samples of the same material. It is possible to obtain maps of porosity in a large object by moving the sensor and making local measurements in different areas. In this context, work is in progress to develop an automated scanning system that should be able to produce porosity maps in a reasonable interval of time.

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