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Technological Process to control the Foam Dielectric Constant

Application to microwave components and antennas

J. Bor, O. Lafond, *Member, IEEE*, H. Merlet, P. Le Bars, *Member, IEEE*, and M. Himdi

Abstract—A technological process to control the foam dielectric constant, an important issue for the design of microwave components and antennas, is described. For that purpose, the use of different commercial foam materials has been considered. This kind of foam substrate is made of original material (PVC, resin, ...) into which gas is injected. So the dielectric constant of such foam is close to 1. It can be increased by expelling the gas out of the foam material. The authors are presenting the technological process used to expel the gas by pressing a foam slab at relatively low temperature (90°C). Thanks to this technological process, the dielectric constant variation can be controlled by the ratio between the initial and final slab thickness. It holds a great interest for the design of microwave antennas and circuits. Indeed, the dielectric constant inside gradient index lenses (Luneburg, Maxwell fish-eye and Fresnel lenses) must follow a particular law to obtain the desired radiation capabilities. Results of materials characterization are presented to validate the technological process. Foam based antennas and components are also shown to illustrate the interest of the process.

Index Terms— Foam material, controlled dielectric constant.

I. INTRODUCTION

MATERIALS with controllable permittivity are mainly used for electromagnetism and chemistry. Foam and composite materials exist with different dielectric constants [1, 2]. They can be used as a support or directly to design microwave circuits or antennas [3]. The foam material used in [3] has the particularity to offer low dielectric constant (close to 1). This allows for the designing of antennas with high efficiency. This kind of foam is composed of basic initial PVC material into which air is injected or special gas. In microwave applications, substrate integrated non radiative waveguides can be manufactured with a particular dielectric constant material [4]. In such applications, it could be interesting to adjust the dielectric constant for different waveguides and so to design phase shifters for example. In microwaves, antennas with inhomogeneous lenses can be designed to focus the radiation pattern [5] [6] [7] but such lenses (Fresnel-zone plate lens, Luneburg lens, Maxwell fish-eye lens and Rotman lens)

require the use of materials with different dielectric constant. For this kind of lens, the objective is to simplify the manufacturing and to reduce the cost by using only one material with controlled dielectric constant. The authors investigate a new and simple technological process to control the dielectric constant of a basic foam material. By expelling the gas contained inside a foam slab, the dielectric constant can vary, for example, between 1.3 and 3.2.

In the first part, the technological process is related in details. In the second part, the measurement setup of dielectric constant is presented and results are shown to validate the principle of controlled dielectric constant based on one initial foam material. These experimental results are compared with theoretical data allowing to predict the dielectric constant of the manufactured material. In the third part, several applications at 60 GHz are presented.

II. TECHNOLOGICAL PROCESS

Four different foams are used and tested to validate the technological process [8]. The first two kinds of foams (H200 and HCP50) are sold by Divinycell while the third and fourth ones (two different references of Airex PXc) are marketed by Corematerials.

A. Some instances of the foams used

These materials have dielectric constants close to one because they are filled with small gas bubbles as it is shown in Figure 1 for the H200 foam. There is four kinds of foams feature low dielectric constant and loss, as presented in Table 1. These characteristics are obtained from a free space measurements setup which is depicted in the second part of the paper. Foams are closed-cell foams and are used for their mechanical properties in the field of construction.

TABLE 1
ELECTRICAL PROPERTIES OF THE FOUR FOAMS MEASURED AT 60 GHz

Foam type	ϵ_r	$\tan \delta$
H200	1.23	0.005
HCP50	1.31	0.004
Airex PXc 245	1.31	0.010
Airex PXc 320	1.43	0.014

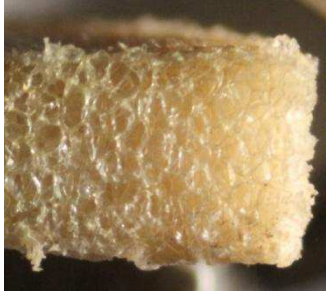


Fig. 1. Cross sectional photograph of a 5mm thick H200 Divinycell Foam.

B. The main idea

In order to determine permittivity of a foam sample, several parameters are involved:

- Density: ρ_x
- Permittivity: ϵ_x
- Volume: V_x
- Thickness: h_x

Where x can be replaced by the appropriate material: g for the gas (air for us), p for the polymer, fi for the initial foam, ff for the final foam.

Two different theories are reviewed: Knott and Plonus theories. The first one used the density and permittivity while the second one is based on the permittivity and volume. Both are computed and compared to measurements.

Firstly, the foam dielectric constant can be predicted by Knott's formula [9]:

$$\epsilon_f = \epsilon_p \left(1 - \frac{(\epsilon_p - \epsilon_g)(1 - \alpha)}{\epsilon_g + (\epsilon_p - \epsilon_g)(1 - \alpha)^{\frac{1}{3}}} \right) \quad (1)$$

Where ϵ_f is the foam dielectric constant, ϵ_p is the dielectric constant of the base polymer, ϵ_g is the dielectric constant of the blowing agent gas (air in our case), and α is the volumetric fraction of polymer in the foam given by:

$$\alpha = \frac{\text{density of foam}}{\text{density of plastic}} \quad (2)$$

The foam density depends on its volume:

$$\rho_f = \frac{M}{S * h} \frac{\text{kg}}{\text{m}^3} \quad (3)$$

Then the main and innovative idea for microwave antennas is to reduce the height of the foam by pressing it (without altering the foam surface area S). When being pressed (Figure 2), the gas is expelled out of the foam, thus increasing the density and the dielectric constant of the foam. The density of the base polymer does not change during the process.

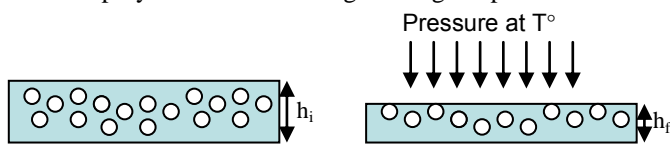


Fig. 2. Illustration of the process to increase foam density.

$$\xi = \frac{\rho_{ff}}{\rho_{fi}} = \frac{h_i}{h_f} \quad (4)$$

The new pressed foam density is given by:

$$\rho_{ff} = \rho_{fi} \xi \frac{\text{kg}}{\text{m}^3} \quad (5)$$

Secondly, as mentioned in [10], knowing the volume ratio, we can calculate the effective relative dielectric constant of pressed foam by (6):

$$\epsilon_f = \frac{\frac{V_g}{V_p} * \epsilon_g + \epsilon_p}{\frac{V_g}{V_p} + 1} \quad (6)$$

Where V_g and V_p are the volume of gas and polymer.

In the reference [10], Plonus finds the volume ratio of gas to base polymer in the foam as a function of foam density and uses this to determine the dielectric constant of the foam.

The equation (7) gives the volume of gas to volume of the base polymer ratio in considered foam knowing the density of base polymer (ρ_p) and gas (ρ_g).

$$\frac{V_g}{V_p} = \frac{\rho_p - \rho_{fi} \xi}{\rho_{fi} \xi - \rho_g} \quad (7)$$

In order to verify the accuracy of the formulas (1) and (6), we used to predict the dielectric constant of H and HCP Divinycell foam [1].

In order to determine the dielectric constant and density of the base polymer (ϵ_p and ρ_p) of each foam material (unavailable data's from manufacturers), the foam samples were powdered (Figure 3a) before being pressed (Figure 3b) to make sure there would be no gas left inside it during measurement. It will thus determine the utmost permittivity and density that can be reached (permittivity of the mixture composed of only core materials without gas). Every references of H or HCP foam (10, 20, 50, 100 ...) are made of the same base polymer; the only difference is the final density of the foam.

- For the gas (air): $\rho_g=1.2 \text{ kg/m}^3$ and $\epsilon_g=1$.
- For H200 foam, the base polymer is PVC material, we measured: $\rho_p=1600 \text{ kg/m}^3$ and $\epsilon_p=3.0$.
- For HCP50 foam, the base polymer is PVC material, we measured: $\rho_p=1500 \text{ kg/m}^3$ and $\epsilon_p=2.92$.
- For Airex PXC 245, the base polymer is glass-reinforced urethane material, we measured: $\rho_p=1075 \text{ kg/m}^3$ and $\epsilon_p=2.8$.
- For Airex PXC 320, the base polymer is the same as PXC 245, but we measured: $\rho_p=1273 \text{ kg/m}^3$ and $\epsilon_p=3.15$.



Fig. 3. Picture of the powdered foam (a) and pressed foam (b)

The formulas (1) and (6) compared to measurements of permittivity (10 GHz in the data sheet) show a good agreement. The measurements are made for different references of foams using the same base polymer but with different densities. Figure 4 and Figure 5 show this agreement

for both Divinycell foams (Airex does not present those values in their data sheet).

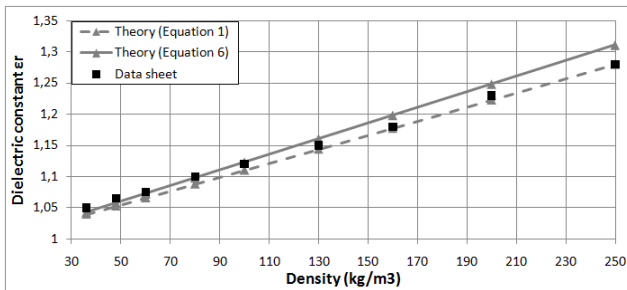


Fig. 4. Dielectric constant law versus density for H Divinycell foam

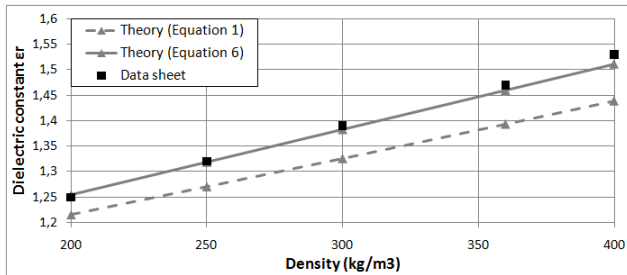


Fig. 5. Dielectric constant law versus density for HCP Divinycell foam

C. Pressing process

The first important parameter is the adjustment of the temperature during the pressing process. An optimized temperature compromise has to be determined in order to avoid melting and burning (with a too high temperature) or to avoid the sample to change size once pressure ceases (if temperature was not high enough). The optimized temperature depends on the type of foam material that is used. The second important parameter is the duration of the pressing. It can vary depending on the foam and will affect the stability of the foam. A sufficient pressing period is needed for the sample to keep its size after pressure. The temperature inside the whole sample of foam must be evenly spread.

For the four kinds of foams mentioned above, the samples are pressed during 20 minutes at 90°C.

A picture of a foam sample before and after being pressed is featured in Figure 6 and Figure 7. A stepped sample with different thicknesses has been pressed. In the figure 7, it is easy to see that the air bubbles have been expelled from the foam after pressing. The density of the foam material is higher after pressing because air has been expelled.

In the next section are presented the results of dielectric constant characterization for different initial thicknesses of foam and with the same final thickness (3mm).



Fig. 6. Stepped sample before being pressed (5, 10, 15mm).



Fig. 7. Stepped sample after being pressed at 5mm.

III. CHARACTERIZATION

A. Free space measurement setup

The measurement of dielectric constant is performed by using a free space measurement [11, 12] bench (Figure 8), composed of an ABmm Vector Network Analyzer (working between 8 GHz and 75 GHz) and a computer with software to extract the dielectric constant from measurements. The free space setup consists of two horns associated with two polyethylene biconvex lenses in order to obtain a focusing plane where the sample under test is placed. The computation of dielectric constant can be obtained either from reflexion (S11) or from transmission measurement (S21), the latter being used in this paper. Permittivity and loss tangent can be determined with formulas given in [13] and [14]. First, the bench is calibrated without any sample. Then, the same measurement is carried out with the sample under test and measurements results are computed in order to find out the dielectric constant of the sample.

This measurement process is fast but limited in terms of bandwidth by the size of the horns and lenses (from 46 GHz, up to 74 GHz). It also requires samples at least a few millimeters thick and with a diameter at least greater than five lambda. To ensure stable results, the whole band has to be measured and results are given at the middle frequency of the band (60 GHz here).



Fig. 8. Photograph of the free space measurement setup composed of horn-lens antennas and support of sample under test.

B. Experimental results of electrical properties

Measurements are done in the V band and electrical properties are given at 60 GHz. The foam samples have been pressed at 90°C during 20 minutes. The final thickness of samples is consistently 3mm after pressing. The four different foams have been characterized using the same method and results of pressed foam dielectric constant versus densities

ratio ξ are plotted in Figures 9, 10, 11 and 12. The values of density and permittivity of base polymer are available section II.b for all foam material.

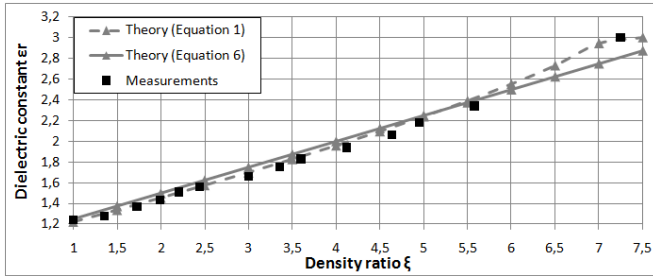


Fig. 9. Dielectric constant law versus densities ratio for pressed H200 foam.

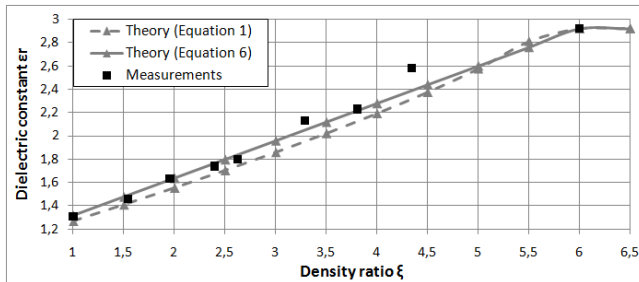


Fig. 10. Dielectric constant law versus densities ratio for pressed HCP50 foam

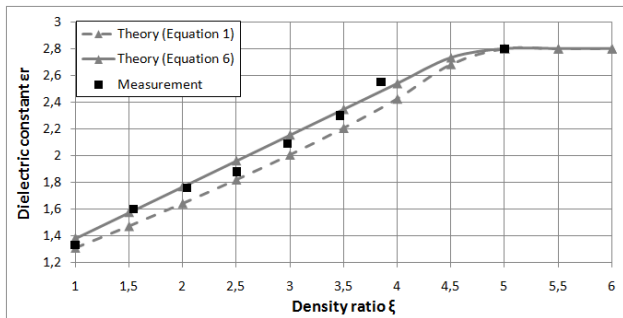


Fig. 11. Dielectric constant law versus densities ratio for pressed Airex PXc245 foam

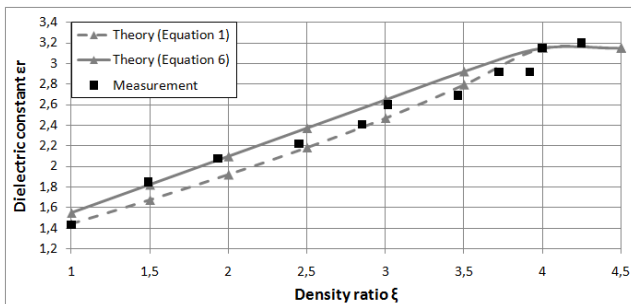


Fig. 12. Dielectric constant law versus densities ratio for pressed Airex PXc320 foam

The results show that it is possible to increase the dielectric constant from 1.33 to 2.8 for the Airex PXc245 foam and 1.43 to 3.15 for the Airex PXc320. For the H200 foam, the range of dielectric constant is reached from 1.22 up to 2.35 and from 1.3 to 2.2 for the HCP50 foam.

IV. MICROWAVES APPLICATIONS

In this section, applications on microwaves components and antennas are presented.

Several applications require a control of the dielectric constant. Non-radiative waveguide is a simple one. It is composed of a dielectric waveguide with two parallel metal plates above and below it. A 3dB/90° dielectric coupler has been manufactured at 30 GHz (Figure 13 and 14) with Airex PXc 245 and a permittivity of 2.1 inside the waveguide has been reached (after being pressed) while the dielectric constant is 1.33 outside of the waveguide.



Fig. 13. Dielectric coupler at 30 GHz before being pressed

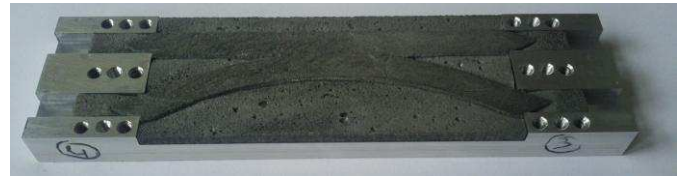


Fig. 14. Dielectric coupler at 30 GHz after being pressed without

Lens antennas are another example where dielectric constant must be control. Fresnel lens or metallic lens require several areas with fixed permittivities. Luneburg and Maxwell fish-eye lens require a gradient index inside the lens. A Luneburg lens has been manufactured at 60GHz as shown Figure 15. Inside the lens, the permittivity ranges from 1 to 2 (for a perfect lens) from the edge of the lens to the centre of the lens. It is made of 6 areas, one with a ring of Rohacell foam ($\epsilon_{r1}=1.05$) and five areas made of one piece of foam ($\epsilon_{r2}=1.33$, $\epsilon_{r3}=1.46$, $\epsilon_{r4}=1.62$, $\epsilon_{r5}=1.77$ and $\epsilon_{r6}=1.92$).

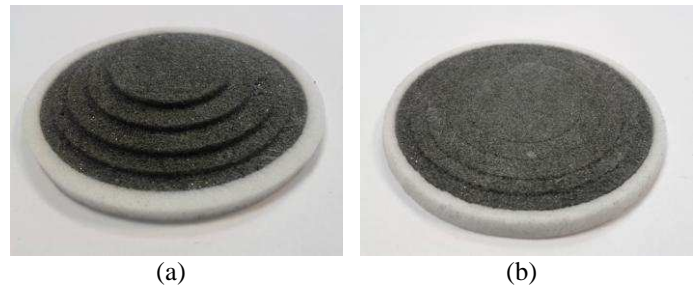


Fig. 15. Foam lens before (a) and after (b) being pressed

V. CONCLUSION

A technological process to design foam material with controlled permittivity has been presented and validated by measurements. The process is simple, inexpensive and materials are lightweight. The permittivity range is limited by the core material properties.

Although four types of foams have been investigated, the proposed process is general.

This technology can be directly applied to the design of microwave components and antennas. It makes for instance the manufacturing of gradient index lenses much easier as detailed in a forthcoming publication.

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REFERENCES

- [1] Divinycell, www.diabgroup.com.
- [2] Airex Baltek, www.corematerials.3AComposites.com.
- [3] S. Chainon, "Etude et conception d'antennes composées de guides d'ondes en technologie mousse métallisée. Applications aux antennes à balayage électronique", Dissertation at the University of Rennes 1, France, 2002.
- [4] F. Xu, K. Wu, "Substrate Integrated Nonradiative Dielectric Waveguide Structures Directly Fabricated on printed Circuit Boards and Metallized Dielectric Layers," IEEE Transactions on Microwave Theory and Techniques, Vol. 59, No 12, December 2011.
- [5] H. D. Hristov, H. A. J. Herben, "Millimeter-wave Farsnel-zone plate lens and antenna," IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 12, Dec. 1995
- [6] B. Fuchs, O. Lafond, S. Palud, L. Le Coq, M. Himdi, M. C. Buck and S. Rondineau, "Comparative Design and Analysis of Luneburg and Half Maxwell Fish-Eye Lens Antennas," IEEE Transactions on Antennas and Propagation, vol. 56, no. 9, Sept. 2008.
- [7] L. Schulwitz, A. Mortazawi, "A new low loss Rotman lens design using a graded dielectric substrate," IEEE Transactions on Microwave Theory and Techniques, Vol. 56, No. 12, Dec. 2008.
- [8] H. Merlet, P. Le Bars, O. Lafond, M. Himdi, "Manufacturing method of a dielectric material and its application to millimeter-waves beam forming antenna systems," patent WO2013083794, June, 2013.
- [9] E. F. Knott, "Dielectric constant of plastic foams," IEEE Transactions on Antennas and Propagation, Vol. 41, No. 8, pp. 1167-1171, August 1993.
- [10] M. A. Plonus, "Theoretical investigations of scattering from plastic foams," IEEE Transactions on Antennas and Propagation, Vol. 13, no. 1, pp. 88-94, January 1965.
- [11] G. L. Friedsam and E. M. Biebl, "A Broadband Free-Space Dielectric Properties Measurement System at Millimeter Wavelengths," IEEE Transactions on Instrumentation and Measurement, Vol. 46, No. 2, April, 1997.
- [12] ABmm, www.abmillimetre.com.
- [13] D. Bourreau, A. Pédén and S. Le Maguer, "A Quasi-optical Free-Space Measurement Setup Without Time-Domain Gating for Material Characterization in the W-Band," IEEE Transactions on Instrumentation and Measurement, Vol. 55, No. 6, December 2006.
- [14] D. K. Ghodgaonkar, V. V. Varadan and V. K. Varadan, "Free-Space Measurement of Complex Permittivity and Complex Permeability of Magnetic Materials at Microwave Frequencies," IEEE Transactions on Instrumentation and Measurement, Vol. 39, No. 2, April 1990.



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His research activities deal with passive and active millimeter-wave multilayer antennas and circuits, reconfigurable antennas, inhomogeneous lenses for shaping radiation patterns with active devices, imaging antenna systems.



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