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To cite this version:

Sylvain Chenu, Jean-Philippe Coupez, Florent Karpus, Baptiste Toublanc. Development of new technologies using foam materials for RF device integration. EuMC 2013: 43th European Microwave Week 2013, Oct 2013, Nuremberg, Germany. pp.326-329, 10.23919/EuMC.2013.6686657 . hal-00934312

HAL Id: hal-00934312

https://hal.science/hal-00934312v1

Submitted on 30 Mar 2022

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Development of new technologies using foam materials for RF device integration

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***Abstract* — This paper deals with results concerning the development of new innovative and competitive technologies for RF device integration, especially hybrid technologies using plastic foam materials. In addition to their relative transparency to microwave signal propagation, these materials have a lot of very interesting properties: weight, cost, ability to be shaped or moulded, ability to be used as a mechanical support as well as a propagation medium. Moreover, these materials have remarkable intrinsic properties in terms of physical, mechanical, thermal and chemical properties. In this context, it is essential to have a good knowledge and an advanced process control of these technologies in order to be best able to satisfy the RF device integration requirements. This paper presents the technological process and performances of microwave devices using foam materials, such as waveguide and printed structures.**

Keywords — foam material; RF applications; ultra-lightweight device; shaping/moulding process; metallization/etching process;

I. Introduction

The work presented in this paper is part of a project, called DENOTEIC, bringing together leading academic and industrial partners to develop practical solutions to metallize foam materials for RF applications. The main issue is to develop an industrial technology process using original plastic foam materials, with the possibility to combine them with more classic materials such as ceramics or polymers. The proposed solutions should make it possible to design microwave devices to meet high requirements in terms of performance and integration, and that allow a high frequency use at least until millimeter-wave.

Many works referring to foam materials have already been published, mainly with reference to waveguides and cavity filters [1]-[2], waveguide to microstrip transitions [3]-[4], and antennas [5]-[6]-[7]. However, foam devices are often prototyping solutions contrary to other existing technologies such as the LPKF-LDS process, which proposes an industrial 3D selective metallization process for plastic material.

II. Foam material specifications

Some foam materials are commonly used to design microwave devices, such as for example Rohacell®, Eccostock® or Divinycell foams. They are used for their very interesting dielectric properties very similar those of vacuum: low dielectric constant and low dielectric losses. However, these materials are relatively expensive. Although these foams offer very interesting properties, they do not necessarily meet our specific requirements, namely:

- A relative transparency to microwave propagation

A material with a low dielectric constant (ε_r<2) and low dielectric losses ($tg\delta$#10^{-3}) on a wide frequency range until millimeter-wave.

- A low density

A material with a low density (#100kg/m^3) in order to realize ultra-lightweight devices.

- A good surface state

A material with an adequately smooth surface to ensure a high quality of metallization and etching, to allow devices use at high frequency.

- A shaping and moulding ability

A material that can be used both as a mechanical support as well as a propagation medium, being easily shaped and moulded following standard processes with high accuracy (#10µm) and the ability to make complex shapes.

- Metallization compatibilities

A material with a wet chemical metallization process which can be etched according to classical techniques and compatible with some requirements such as materials bonding and components mounting.

III. Properties of foam materials

We characterized a set of 13 commercially available foams from various application domains (rail, aviation, maritime, oil) which cover a fairly wide range of products (Fig.1).

Fig. 1 **Left:** Overview of the 13 foam samples studied (from left to right): Rohacell® 71HF, C-Therm, Hyperlast™, Compaxx™, Divinycell H100, Divinycell HCP100, Airex®, Eccostock® LoK, Eccostock® SH8, Saitpur, MHD350, MHD220 and MHD130. **Right:** Waveguides and associated foam inserts to characterize at X and Ka bands. WR-90 (resp. WR-28) waveguide dimensions: 10.16 x 22.86 x 65 mm^3 (3.56 x 7.11 x 50 mm^3).

Waveguide structures are particularly well-suited for material characterization (Fig.1). The method of characterization involves determining dielectric properties of foams – data not known a priori for most of them – by reverse-simulation from S-parameters measurement of a foam-filled waveguide. And that for two frequency ranges:

- At X-band i.e. 8 to 12 GHz (centimetric wave)
- At Ka-band i.e. 26.5 to 40 GHz (millimetric wave)

Following the characterization of the foam samples studied, we were able to select the most suitable one, the polyurethane

MHD130 foam from Saitec Company [8], which has high level dielectric properties (ε_r=1.17, $tg\delta$=0.003), very good chemical resistance, low density and low cost.

IV. METALLIZATION PROCESS

Metallization of foam materials involves developing a process which must be stabilized, reliable and easy to carry out in order to ensure its reproducibility on a large scale in the context of industrial development. This is developed by one of our industrial partners: Protecno Company from the GTID Group. Such a process involves technical know-how and an advanced metallization process control at different levels:

- Control of the deposit thickness
- Adequate surface smoothing of the material
- Resolution and accuracy for etching and via holes

We carried out waveguides at X and Ka bands with two metallization processes to compare them:

- Protecno – electrolytic copper plating
- Spraylat – silver conductive coating (paint) deposit

And compared results with a raw foam-filled waveguide.

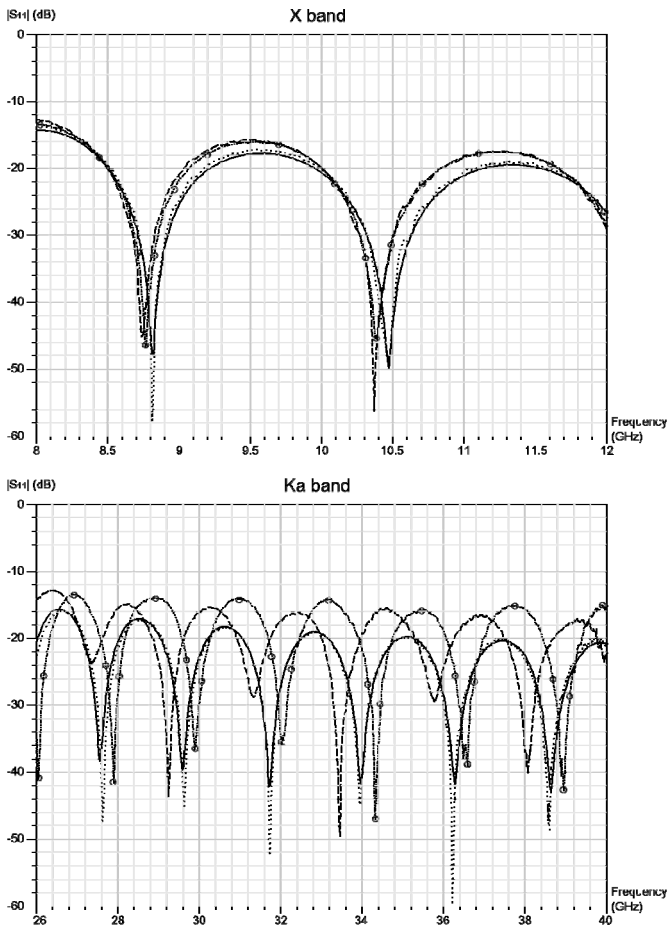


Fig. 2 S_{11}-parameters of MHD130 foam waveguides at X-band and Ka-band. **Line style: solid** simulation – **dotted** raw foam insert – **dashed** Spraylat metallization with varnish – **circular marker at X (resp. Ka) band** Protecno metallization with (resp. without) varnish.

The results shown in Fig.2 correspond to MHD130 foam waveguides. For this material, the roughness requires a surface preparation step before the metallization process, using a varnish to fill gaps in order to obtain a smoother surface. As a consequence, a slight shift to lower frequencies is observed for both frequency bands, especially in Ka-band. Indeed, the varnish application increases the permittivity of the material locally (i.e. at the surface), therefore the resonant frequencies decrease. In the future, an improved method by spray coating will be substituted, provided a thinner and more homogeneous varnish layer. Without varnish coating, the MHD130 raw foam roughness is estimated at ~100µm. Such a value has little influence on centimetric devices contrary to millimetric ones, which are more affected by material defects. Indeed, as we can note in Fig.2, the resonant frequencies of the Ka-band waveguide without varnish increase due to the metallization penetration which results in an apparent reduction of the waveguide cross section.

The waveguide losses have been measured to 0.04dB/cm for the X-band foam-filled waveguide and 0.05dB/cm (resp. 0.06dB/cm) with Protecno (resp. Spraylat) waveguide metallization process. At Ka-band, these values are equal to 0.15dB/cm, 0.20dB/cm and 0.25dB/cm.

V. RF AND MICROWAVE DEVICES

The validation and the development of an industrial technology process using foam materials involves realizing some basic microwave devices, such as those shown in Fig.3, to demonstrate all its potential.

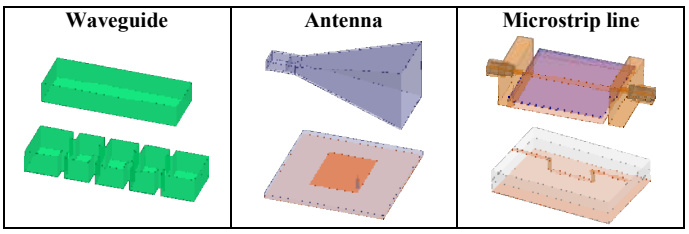


Fig. 3 Examples of RF devices using foam materials.

A. *Iris waveguide filter*

As standard waveguides, iris waveguide filters are also interesting devices to study. 1st, 2nd and 3rd order filters have been realized. Only the 3rd order filter responses are shown in Fig.4 at X and Ka bands. The results are quite similar for other orders.

As we can show in Fig.4, we have very good agreement between measurement and simulation results. However, we note that the Ka-band measured filter responses are shifted to higher frequencies, due to the apparent reduction of the waveguide cross section of the filters without varnish. This result is consistent with our observations in the last section and has been confirmed by simulation.

The -10dB bandwidth is about 5% for both frequency bands and losses are close to 1dB (resp. 3dB) in X-band (resp. Ka-band). Note that metallization quality could be yet improved to decrease losses.

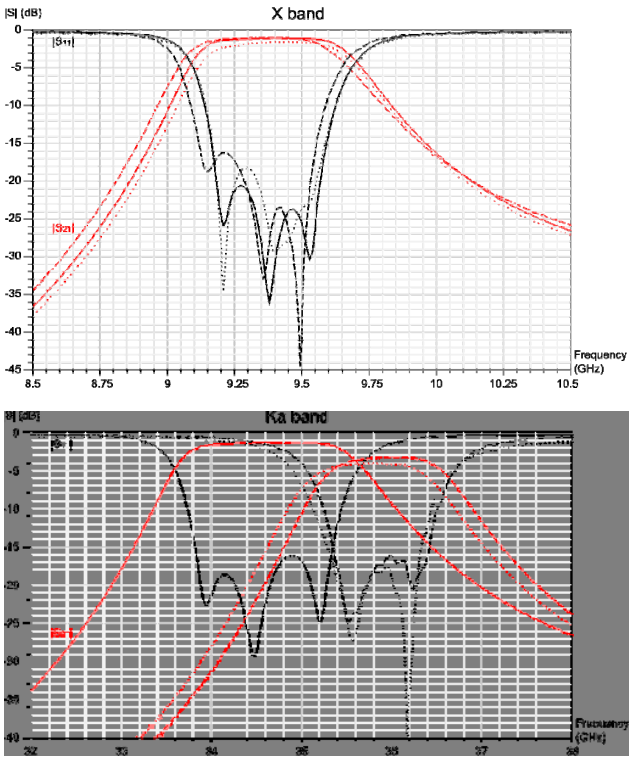
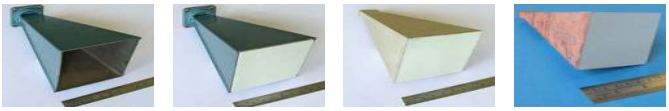


Fig. 4 S-parameters of 3rd order MHD130 iris waveguide filters at X-band and Ka-band. **Line style: solid** simulation – **dotted** Spraylat metallization – **dashed** Protecno metallization.

B. Horn antenna

Antennas are other microwave devices which are of great interest. Therefore some horn antennas have been realized using MHD130 foam, at X-band (Fig.5) and Ka-band (Fig.7).



a. G=17.5dBi **b.** G=17dBi **c.** G=17.2dBi **d.** G=17.3dBi

Fig. 5 X-band horn antennas and associated gain: **a.** reference – **b.** reference with foam insert – **c.** Spraylat metallized foam – **d.** Protecno metallized foam.

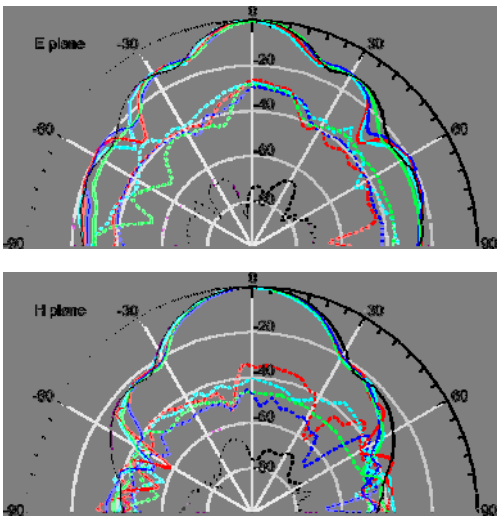
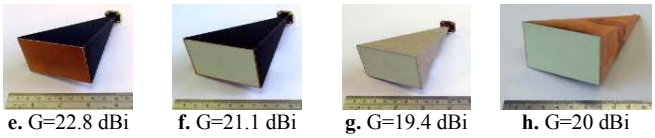


Fig. 6 Normalized polar radiation pattern of co (solid line) and cross (dashed line) polarization, in E plane and H plane at 10GHz. **Line style: a.** green – **a. simulated** black – **b.** blue – **c.** red – **d.** skyblue.

Concerning the X-band horn antennas, the matching level is always lower than -15dB over the band. Simulated gain result of the reference antenna without (resp. with) MHD130 foam insert is 18.1dBi (resp. 17.5dBi) that is close to the measured gain values as indicated in Fig.5. Radiation patterns are very similar for all antennas as we can show in Fig.6. The half-power$_{-3dB}$ beamwidth (HPBW) measurement of antennas in E plane is 18°±1 compared with the simulation of the reference antenna which is 21°. In H plane, the HPBW measurement of antennas is 25°±1 compared with the simulation value equal to 27°. And the co/cross polarization ratios in the end-fire direction are both less than -25dB.



e. G=22.8 dBi **f.** G=21.1 dBi **g.** G=19.4 dBi **h.** G=20 dBi

Fig. 7 Ka-band horn antennas and associated gain: **a.** reference – **b.** reference with foam insert – **c.** Spraylat metallized foam – **d.** Protecno metallized foam.

In a same way, we have realized horn antennas at Ka-band. The matching level is always lower than -15dB over the band. Simulated gain result of the reference antenna without (resp. with) MHD130 foam insert is 23.8dBi (resp. 22.1dBi) that is close to the measured gain values as indicated in Fig.7. Radiation patterns are very similar for all antennas as we can show in Fig.8. The HPBW measurement of antennas in E plane is 11°±1 compared with the simulation of the reference antenna which is 11°. In H plane, the HPBW measurement of antennas is 13°±1 compared with the simulation value equal to 12°. And the co/cross polarization ratios in the end-fire direction are both less than -25dB.

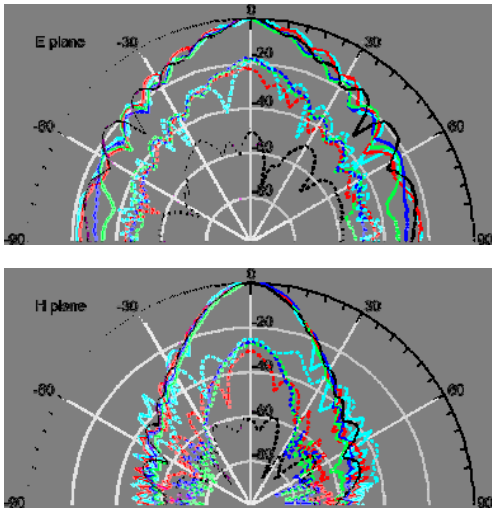


Fig. 8 Normalized polar radiation pattern of co (solid line) and cross (dashed line) polarization, in E plane and H plane at 35GHz. **Line style: e.** green – **e. simulated** black – **f.** blue – **g.** red – **h.** skyblue.

C. Patch antenna

Patch antennas are also of interest because they require selective metallization. However, the present surface state of the MHD130 foam does not yet give high quality metallization for conventional etching techniques. Therefore some patch antennas have been realized by mechanical micromachining of the top metallized layer (Fig.9).

Spraylat metallization

G=7.3dBi

Protecno metallization

G=7.6dBi

Fig. 9 5GHz patch antennas and associated gain. Patch size: 27 x 25 mm^2 – Substrate size: 60 x 50 mm^2 and thickness: 3mm – Offset feeding probe: 7mm.

The matching level is always lower than -20dB over the band. Simulated gain result of this patch antenna is 8.9dBi that is relatively close to the measured gain values (7.6dBi).

Radiation patterns are very similar for all antennas as we can show in Fig.10. The HPBW measurement of antennas in E plane is 59°±1 compared with the simulation of the reference antenna which is 62°. In H plane, the HPBW measurement of antennas is 61°±1 compared with the simulation value equal to 60°. And the co/cross polarization ratios in the end-fire direction are both less than -20dB.

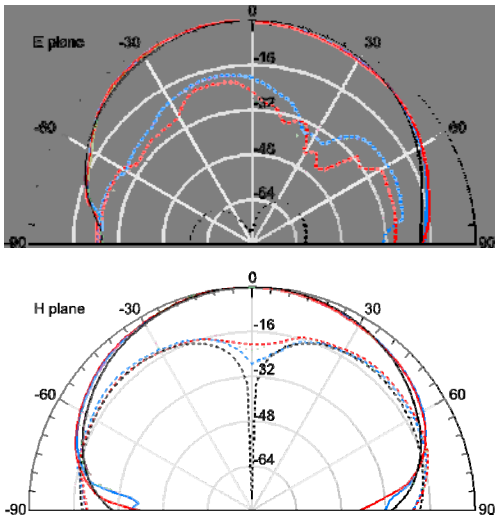
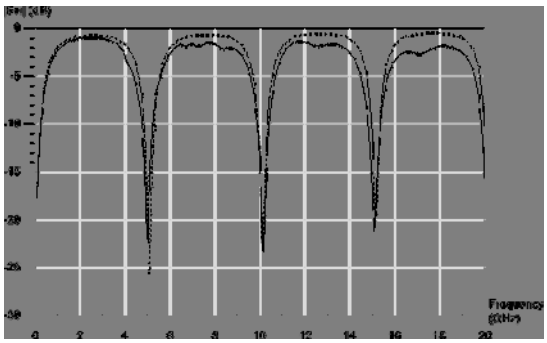


Fig. 10 Normalized polar radiation pattern of co (solid line) and cross (dashed line) polarization, in E plane and H plane at 5GHz. **Line style: black** simulation – **red** Spraylat metallized – **blue** Protecno metallized.

D. Microstrip transmission line

Currently, microstrip lines have also been realized by surface micromachining. These are deliberately unmatched in order to characterize losses and resonances of the microstrip lines. It constitutes a complementary materials characterization technique with regard to the waveguide approach.

Here are shown only the measurement results of a microstrip line on the MHD130 foam. As we can show in Fig.11, we have very good agreement between measure and simulation results. The observed magnitude variation at high



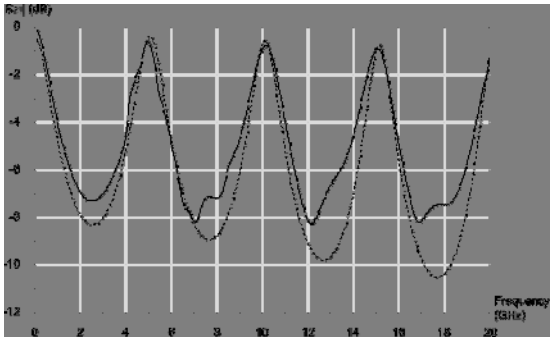


Fig. 11 S-parameters of a resonant microstrip line (length: 28mm, width: 500µm) on MHD130 foam substrate (thickness: 5mm), characteristic impedance Zc=241Ω. **Line style: solid** measure – **dotted** simulation.

frequency is due to the degradation of the interconnections between the measurement cell and the microstrip line, considering the relatively high substrate thickness. It results in the same dielectric properties (ε_r=1.17, $tg\delta$=0.003), as those obtained by a waveguide characterization.

VI. Conclusion

The DENOTEIC project aims to develop an industrial innovative and competitive technology process, using original materials which are plastic foam materials, in order to integrate low cost and ultra-lightweight RF devices. Indeed, as we have seen, foam materials have very interesting properties in addition to their relative electrical transparency: weight, cost, ability to be shaped and moulded, ability to be used as a mechanical support as well as a propagation medium.

To validate our process, we have realized different basic microwave devices, illustrating the whole potential of the technology, such as waveguides, antennas and microstrip structures. We obtained very good results for devices operating until millimeter-wave. Our final objective is to design a complete RF module integrating a lot of functions, each of them using foam materials. We also continue to develop new RF devices to complete our showcase and our technological know-how (for instance, microstrip filters, waveguide to microstrip transitions or stacked patch antenna).

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