Dielectric Analysis of 3D Printed Materials for Focusing Elements Operating in Mm & THz Wave Frequency Bands

B. Zhu[1] J. Stiens[1] G. Poesen[1] S. Vanloocke[2] D. De Zutter[2] R. Vounckx[1]

[1] Laboratory for Micro- and Photon electronics, Department of Electronics and Informatics, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Elsene, Belgium

[2]Department of Information Technology (INTEC), UGent, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

In near-field microscopy at millimetre and THz wave frequencies, it is essential to design focusing elements featuring sub-wavelength dimensions. Teflon has been a very popular material for designing dielectric waveguides, however, it is difficult to mill or cut focusing elements with (sub)-millimetre dimensions due to its softness. Hence, a new method, based on additive manufacturing technology, e.g. the Dimension Elite 3D printer, is introduced. The material and structure of 3D printed products is analysed by means of broad band dielectric spectroscopy using a Quasi-optical Millimetre wave vector network analyser (MVNA) operating in the 40 to 330 GHz range. A comparison between 3D printed ABS with Teflon is presented and the possible millimetre wave applications are finally discussed.

1 Introduction

Scattering scanning near-field microscopy imaging is a powerful technique to obtain sub-wavelength resolution images of a sample. The method is based on measuring the scattered near-field very close to a sample or converting the near-field evanescent wave to propagation wave and detected in far field. The amplitude and phase of this near field are highly dependent on the local structure and therefore contain very high resolution spatial information. However, extracting this information from the scattered fields requires near-field probes capable of coupling to the local field at a tiny point. The higher the resolution, the more sophisticated and expensive the probes are [1]. Recently, many groups have demonstrated different imaging probe technique, such as aperture probes and aperture-less probes, particularly, a circular aperture, a modulated scatter probe, a coaxial cable, an open waveguide, a small loop, and a micro-strip resonator, a narrow resonant slit, a metal micro-slit probe, a thin-slit aperture in a convex and plate of a rectangular wave guide, resonant waveguide probe [2] and so on.

Although many probes are mentioned above, the highest resolution probes were various sharp metallic tip and dielectric waveguides of sub-wavelength aperture sizes and were placed within 0.5 mm of the sample surface. Conical Teflon probes in [1] get 0.2 to 0.5 mm resolution at 260 GHz and 0.5 mm resolution at 150 GHz in [3]. Teflon is widely used in dielectric waveguides because of its low loss in millimetre wave frequencies, but it is hard to mill or cut sub-millimetre dimensions on a lathe due to its softness. It should be attractive to find some substitute material of Teflon to increase the resolution and enlarge more millimetre wave applications. 3D printing is popular in the industrial design thanks to its additive manufacturing and rapid prototyping technology. The Dimension Elite 3D printer is employed in this work. The principle of its working process and the structure of its products are analysed in part 2; the dielectric characterization results of the 3D printed materials is presented in part 3; A comparison of 3D printed ABS tip and Teflon tip in the near-field imaging system is shown in part 4 and the possible millimetre wave applications are finally discussed.

2 3D printing and P430 ABS plus

3D printing is a form of additive manufacturing technology where a three dimensional object is created by successive layers of some material. Recently, 3D printers have become financially accessible to small and medium size, thereby taking prototyping out of the heavy industry and into the office environment. It takes fewer hours, less tools and even no skilled mechanical labour. The Dimension Elite is ideal for printing intricate 3D product mockups and functional models. Using ABS plus™ production-grade thermoplastic, the Elite prints models from the bottom up with precisely deposited layers of modelling and support material. A water-based solution removes the support material to complete the detailed design. Then models can be drilled, tapped, sanded and painted. The resolution (layer thickness) can reach 0.178 mm.
ABS (Acrylonitrile butadiene styrene) is a common thermoplastic used to make light, rigid, molded products such as piping, musical instruments, golf club heads and so on. It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene, the proportions can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. The permittivity is from 2 to 3.5, the loss tangent is from 0.005 to 0.019 reported by MatWeb, a website for material property data. When combined with a Dimension Elite system, P430 ABS is ideal for 3D printing of models in the engineering office.

3 Dielectric analysis of P430 ABS plus

The measurement procedure in this paper is fully automated using the AB millimeter 8-350-2 VNA (MVNA). The Quasi-optical mm-wave reflection and transmission setup is introduced in [4] and [5]. The permittivity and loss tangent can be fitted from the phase variation and from the periodicity of the sample behaving as a Fabry-Perot resonator. V-band (44-74 GHz), W-band (62-112 GHz), D-band (108-170 GHz) and High band (220-330 GHz) experiments are carried out. The slab sample’s thickness is measured by Mitutoyo corp. with a resolution of 1 µm and a range of 50.08- 0.001 mm and an accuracy of 0.006 mm.
As can be seen from Fig. 1, in V, W, D-band, the permittivity and loss decrease when the slab sample is thicker. Confusingly, the dielectric characteristics seem to be thickness dependent. When we cut the slabs we found it is not a homogenous material, but it has many deep holes; it is a mixture of ABS and air. The inner structure of 3D printed products is shown in Fig. 2. We cut the bottom layer of thicker slabs and got 8.19 mm and 28.29 mm slabs. The permittivity and loss are not affected by the surface of the sample according to a lot of experiments; the rough sample surface just affects the reflection phase. Fig. 3 presents that if the thickness is big enough, the permittivity and the loss should be stable.
According to the structure of the 3D printed slabs, 5 layers structure is defined, composing a full top and bottom layer, a transition layer between the grid and top or bottom layer, a grid layer, respectively. We cut the top, bottom and transition layers; we got bulk, grid layers. By Measuring the weight and volume, the density of grid layers are obtained. The density of ABS is 1060 to 1080 kg/m^3, the air density at 20 °C is 1.205 kg/m^3, the air percentage can be derived. It is 38.28 to 39.42%. According to

Maxwell Garnett Mixing Rule [6], we get the permittivity of the pure P430ABS is 2.84 (when the effective permittivity is 1.91, the air density is 39%).

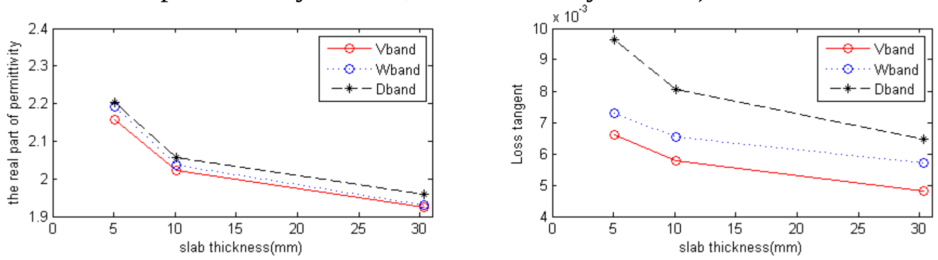

Fig. 1. The real part of permittivity and the loss of 5.12 mm, 10.12 mm, 30.33 mm slabs

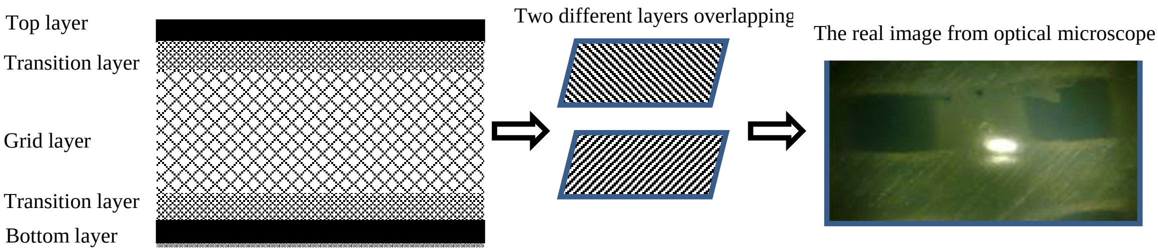

Fig. 2. The inner structure of the 3D printed products. In order to save the material, the 3D printers make structure holes by overlapping different line layers, there are 5 or 6 solid layers in the top and bottom respectively.

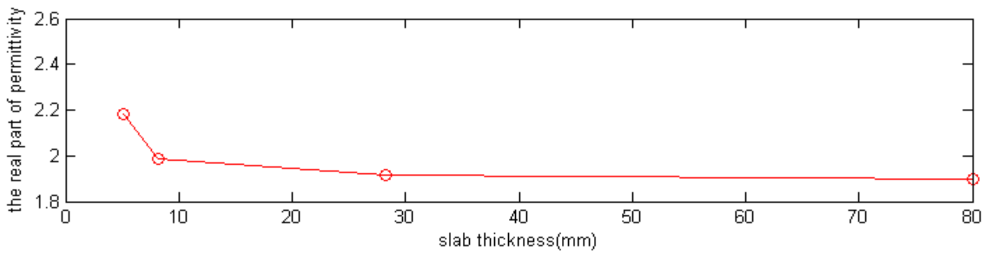

Fig. 3. The permittivity in V band

We conduct the dielectric analysis in a range of 40 to 330 GHz on the sample with top and the sample without top; they are 27.29 mm and 25.13 mm thick, respectively. It is obviously seen that the permittivity and the loss is dependent on the frequency. When the frequency is higher, the loss and the permittivity are higher too. The transmission has a big gap when the frequency is higher than 270 GHz, the high band results below are from 220 to 270 GHz. In [5], Teflon was measured using the same way; the permittivity is 2.03-2.04 in W-band, 1.96-2 at 140 GHz.

Table 1. The permittivity and the loss tangent of different samples with and without top bottom layers in V-band, W-band, D-band, high band (220-270 GHz).

	thickness(mm)	Vband		Wband		Dband		High band	
		tan	ε	tan	ε	tan	ε	tan	ε
1	27,29	0,00499	1,912	0,00753	1,919	0,00753	1,936	0.0140	2.278
2	25,13	0,00475	1,905	0,00678	1,909	0,00751	1,928	0.0139	2.266

4 Comparison with Teflon

Teflon and P430ABS probes are designed in the W-band (70-110 GHz). Simulations were carried out by CST Microwave studio. The results are shown at 90 GHz. The length of the probe is 10mm and the angle of the tip is 45 °. We can put two tips faced together, and from the second receive port, the transmission attenuation is only around

10 db for Teflon and 20 db for ABS in the W-band. Fig. 4 depicts the simple near-field image system based on MVNA. The sample is 1 mm wide metal strips and 1 mm interval on PCB.

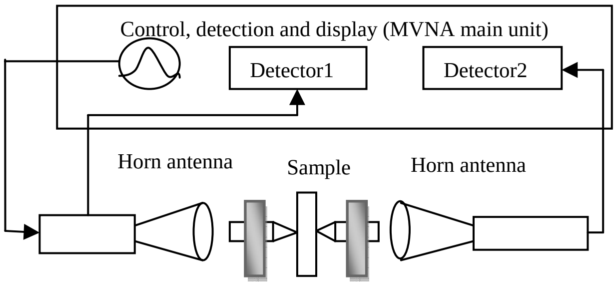

Fig. 4. Experimental setup. The tips are supported by the metal plate and the sample scanning system is controlled by the PI DC-motor controller C-812.02, time sweeping is adopted in this measurement.

ABS can distinguish the 1 mm wide metal strips but the amplitude of the difference between metal strips and PCB interval is lower than Teflon because of the higher loss tangent. Therefore, ABS can be applied in millimetre wave and it can be a substitute of Teflon in Lower band.

5 Conclusion and Discussion

In this paper, the permittivity and the loss tangent of 3D printed material are measured from the scattering parameters using a quasi-optic free space method. It is found that P430 ABS is a medium loss dielectric material. The permittivity and the loss variation depend on the frequency and the thickness. To some extent, it can replace Teflon to play an important role in millimeter wave dielectric wave guides and its applications in low band (40 GHz to 270 GHz). It can also be used for millimeter wave lenses, concentrators and their applications. Especially in near-field microscopy, it can overcome the disadvantages of Teflon, although its loss is higher than Teflon, and increase the resolution.

Acknowledgements

This work was funded by the FWO-Vlaanderen project “FWOAL465- Scattering type near-field mm wave microscopy” of the Flemish region in Belgium and is also executed in the framework of NEWFOCUS ESF Research Networking Program (RNP).

References

[1] M. D. Weiss, B. Zadler, S. Schafer et al., “Near field millimeter wave microscopy with conical Teflon probes,” Journal of Applied Physics, vol. 106, no. 4, 2009.

[2] W. Park, J. Kim, and K. Lee, “Millimeter-wave scanning near-field microscope using a resonant waveguide probe,” Applied Physics Letters, vol. 79, no. 16, pp. 2642-2644, Oct, 2001.

[3] N. S. Greeney, and J. A. Scales, “Dielectric microscopy with submillimeter resolution,” Applied Physics Letters, vol. 91, no. 22, 2007.

[4] A. Elhawil, G. Koers, L. Zhang et al., “Reliable method for material characterisation using quasi-optical free-space measurement in W-band,” Iet Science Measurement & Technology, vol. 3, no. 1, pp. 39-50, Jan, 2009.

[5] A. Elhawil, L. Zhang, J. Stiens et al., “A quasi-optical free-space method for dielectric constant characterization of polymer Materials in mm-wave Band,” in Proceedings of Symposium IEEE/LEOS Benelux Chapter, 187-190,2007.

[6] A. Sihvola,”Mixing rules with complex dielectric coefficients,” Subsurface Sensing Technologies and Applications, vol. 1, no. 4, pp. 393-415, 2000.