Complex Relative Permittivity Measurement of Selected 3D-Printed Materials up to 10 GHz

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***Abstract*—In this contribution, the complex relative permittivity of selected materials for additive manufacturing 3D print technology is measured. The included materials are acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polylactic acid (PLA), XT co-polyester and special material with admixture of cork. The samples for measurement are made by Prusa 3D printer and the manufacturing properties like necessary precision, melting temperature and mechanic properties of each material are discussed. For broadband measurement in the frequency range from 1 to 10 GHz, the transmission/reflection method is exploited. The scattering parameters of material samples located in a N-type male coaxial adapter with air dielectric are measured by vector network analyzer and the complex relative permittivity of measured samples is extracted. The results show that the real part of the relative permittivity of materials is in the range from 2.55 to 2.95 and the imaginary one is from 0.007 to 0.08.**

Keywords—3D printing, 3D printed materials, additive manufacturing, complex permittivity measurements, transmission/reflection measurement method

I. Introduction

3D printing is a fast-growing technology interfering with many industries like aerospace, automotive, healthcare or fashion industry [2]. It can be ideally used for prototyping in research groups or for manufacturing of small product series. The greatest advantages of 3D printing are speed of manufacturing and diversity of printing possibilities. Vice versa of traditional manufacturing, 3D printing is an additive process. 3D printing generally works in one of two principles. The most common way is extruding the material through a tiny nozzle onto a build area. For example, the fused deposit manufacturing (FDM) is based on extruding a melted material through nozzle to build the final structure. The second way is founded on fusing a bed of powdered, sheet or fluid material. Most commonly used materials for 3D printing are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA).

Those materials were in the open literature characterized from the viewpoint of the complex permittivity in the microwave frequency range up to 60 GHz by different methods [3-8].

In this contribution the complex permittivity of most common materials used in FDM like ABS, PLA, polyethylene terephthalate (PET) and less common material XT co-polyester and PLA with admixture of cork, are measured. The measurement is done in the frequency range from 1 to 10 GHz. The obtained data can be exploited for design of microwave circuits and antennas.

II. Characterization Measured Materials

A. Measurement Method

For the measurement, the transmission/reflection (T/R) method is exploited [1]. This method is based on the measurement of the scattering parameters of a sample located in a sample holder by a vector network analyser (VNA) (Figure 1.).

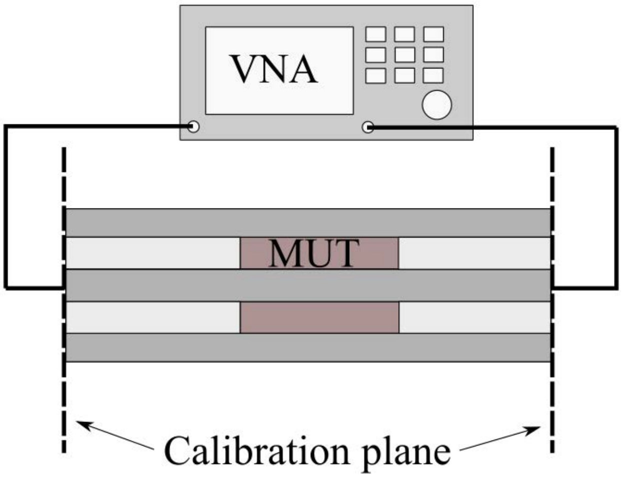

Figure 1. T/R measurement method setup.

The complex relative permittivity

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \qquad (1)$$

can be obtained by solving the following equation [1]

$$S_{21}S_{12} - S_{11}S_{22} = exp[(-2\gamma_0)(L_{air} - L)]\frac{z^2-\Gamma^2}{1-z^2\Gamma^2}, \qquad (2)$$

where $S_{21}S_{12} - S_{11}S_{22}$ is the determinant of the scattering matrix. In the equation (2), γ_0 is propagation constant in air and can be obtained by

$$\gamma_0 = j\frac{\omega}{c}. \qquad (3)$$

Further ω is angular frequency, c is speed of light in air, L_{air} and L are the lengths of the sample holder and the measured sample. The transmission coefficient z can be obtained by

$$z = exp(-\gamma L), \qquad (4)$$

and the propagation constant γ in the measured material

$$\gamma = j\frac{\omega\sqrt{\varepsilon_R^*}}{c}. \qquad (5)$$

The reflection coefficient Γ can be obtained by

$$\Gamma = \frac{\frac{c}{c_{lab}}\sqrt{\frac{1}{\varepsilon_r^*}}-1}{\frac{c}{c_{lab}}\sqrt{\frac{1}{\varepsilon_r^*}}+1}\,. \tag{6}$$

In this equation c_{lab} is speed of light in laboratory environment. This equation is independent to a sample position in the sample holder and valid only for materials with the relative permeability $\mu_R^*=1$.

For our measurement, a N-type male coaxial adapter with air dielectric is used as the sample holder.

B. Materials

The ABS material is a tough and heat resistant thermoplastic polymer. The recommended nozzle temperature during printing for the EasyABS filament is 255 ˚C [9]. Disadvantages of the ABS are worse printing resolution and sensitivity to room temperature during printing. The PET material is the most common thermoplastic polymer. Advantages of the PET are durability and good layer adhesion [9]. The recommended nozzle temperature during printing of PETG filament is 240 ˚C. The PLA material is very easy to print due to low print temperature 215 ˚C but it is also tough and durable [9]. The disadvantage of the PLA is low heat resistance. The XT co-polymer is made with Eastman Amphora 3D polymer [9]. The XT is more durable and heat resisting than PLA. The recommended nozzle temperature during printing is 240 – 260 ˚C. This material has a good adhesion of layers. The Corkfill filament [9] is based on the PLA mixed with cork fibres. For the Corkfill filament it is recommended to use larger nozzle due to the possibility of damaged of regular 0.4 mm diameter nozzle.

C. Sample Preparation

The samples for the measurement were made by a Prusa 3D printer (Figure 2.), which is based on the FDM 3D print technique. The samples were prepared by the 3D printer using concentric rings print style with 100% filling factor. The materials have different behaviours during the printing. The preparation of the accurate ABS sample was difficult due to the material disadvantages. On the other hand, the preparation of the PLA and Corkfill samples was simple. Low printing temperature and good layer adhesion makes the PLA ideal material for 3D printing beginners.

The prepared samples are shown in Figure 3. The outer diameter of the samples is 7 mm and the inner diameter is 3 mm. The samples were adjusted to precision fit in the coaxial adapter which is necessary to get valid results of measurements.

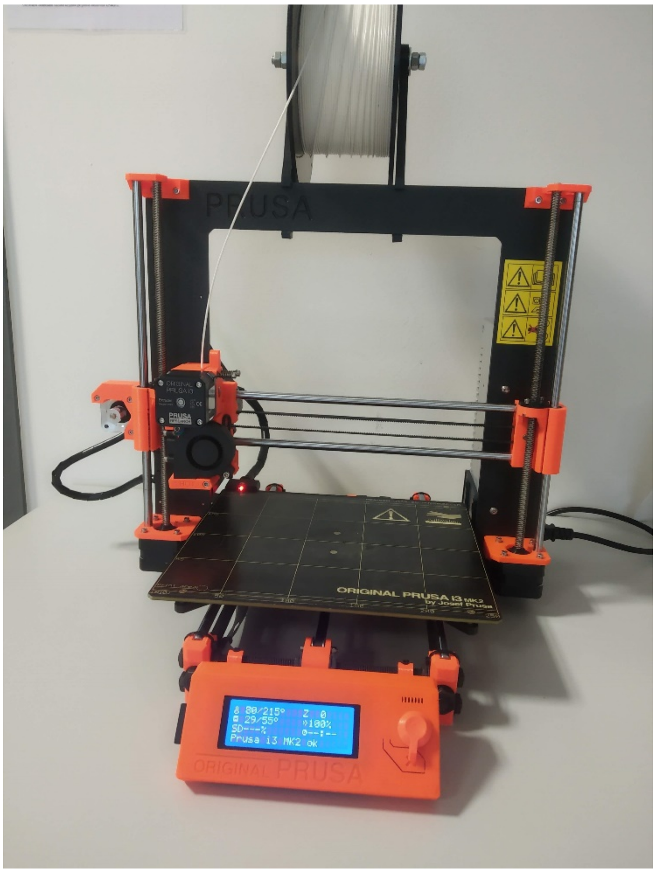

Figure 2. Prusa i3 MK2 3D printer.

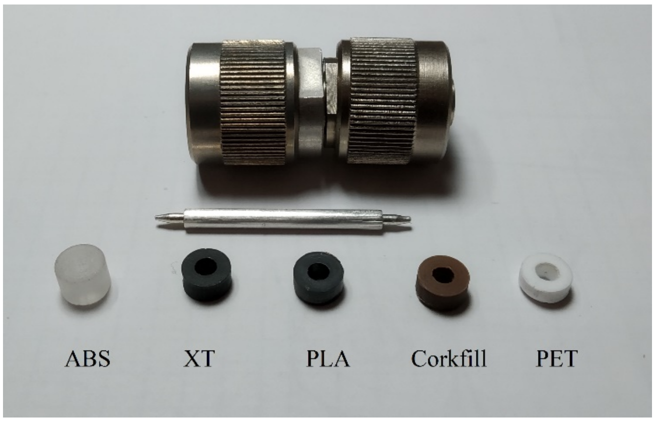

Figure 3. Prepared material samples and coaxial adapter.

III. MEASUREMENT

The results of the measurement are presented in Figures 4-8. The real part of the relative permittivity is in the range from 2.55 to 2.95. The ABS material reaches the lowest values of the real part of the relative permittivity which is about 2.6 (Figure 4.). The ABS material has the lowest imaginary part of complex relative permittivity. On the other hand, the XT co-polyester material (Figure 7.) reaches the highest values of the real part of the relative permittivity which is about 2.91. Both those materials seem promising for microwave applications.

The comparison with the results of the measured ABS, and PLA materials with published in [3], [4], [5], [8] is presented in Table 1.

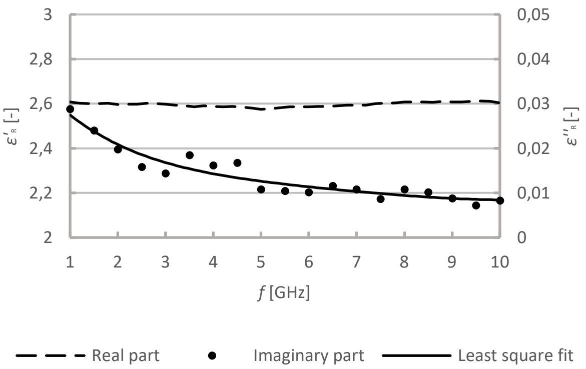

Figure 4. Measured results of complex relative permittivity for ABS.

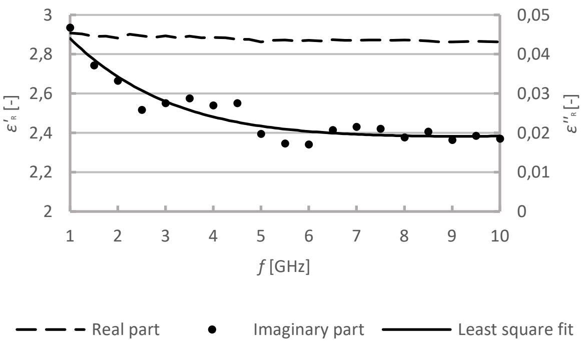

Figure 5. Measured results of complex relative permittivity of PET.

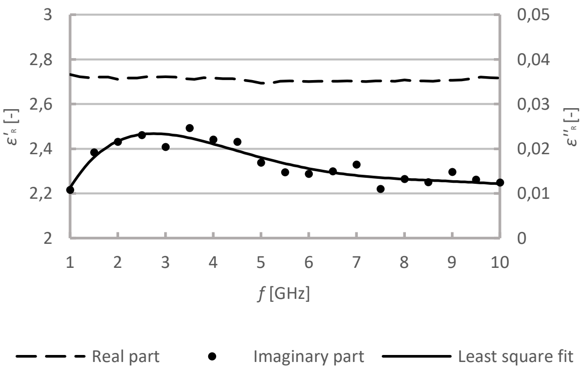

Figure 6. Measured results of complex relative permittivity of PLA.

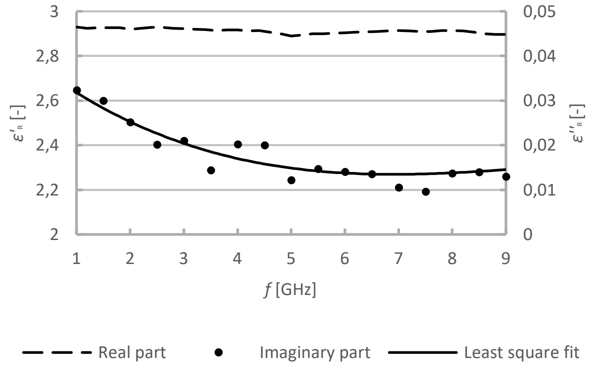

Figure 7. Measured results of complex relative permittivity of XT co-polyester.

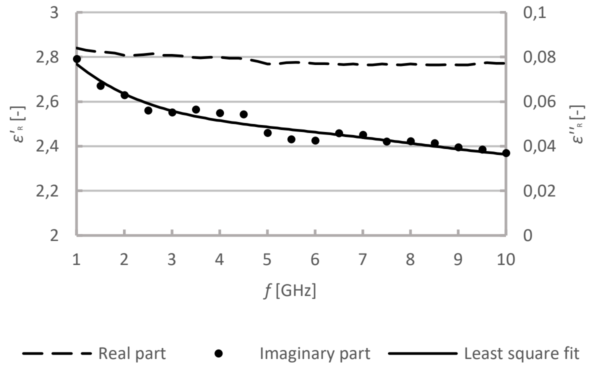

Figure 8. Measured results of complex relative permittivity of Corkfill.

TABLE I. COMPARISON OF MEASURED MATERIALS WITH PUBLISHED VALUES.

Material	Complex relative permittivity				
	Real part [-]		Imaginary part [-]		
	This work	***Referenced***	***This work***	***Referenced***	***Ref. frequency range [GHz]***
ABS	2.6	2.4[4]	0.014	0.0132[4]	30 to 50
		2.8[8]		0.0252[8]	2 to 20
PET	2.87		0.024		
PLA	2.71	2.75[3]	0.017	0.041[3]	DC to 18
		2.57-2.72[4]		0.024-0.027[4]	30 to 50
		2.75[5]		0.03[5]	2 to 20
XT	2.91		0.017		
Corkfill	2.79		0.05		

IV. CONCLUSION

The complex relative permittivity of selected 3D-printed materials, ABS, PET, PLA, XT co-polyester and Corkfill, in the range from 1 to 10 GHz band have been measured by the T/R measurement method. It seem that the ABS and XT co-polyester materials are promising materials for microwave applications.

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