




Complex Dielectric Permittivity of Engineering and 3D-Printing Polymers at Q-Band

Nicolás Reyes¹  · Francisco Casado¹ · Valeria Tapia² · Claudio Jarufe¹ · Ricardo Finger² · Leonardo Bronfman²

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Abstract

We report experimental values of the complex dielectric permittivity of a wide variety of engineering polymers. Measurements were done using the filling waveguide method at Q-band (30–50 GHz), being representative of the values over the millimeter wave regime. This method has a high accuracy, providing excellent wide-bandwidth characterization. Measured samples include the most common engineering materials as polyamide, polyethylene, polytetrafluoroethylene, polyoxymethylene, polylactic acid, phenol formaldehyde resin, polypropylene, polyvinyl chloride, acrylonitrile butadiene styrene, polyphenylene sulfide, and polyether ether ketone. Results are comprehensive and represent an important contribution to the technical literature which lacks of material measurements at these frequencies. Of particular interest are samples of 3D printed materials and high performance polymers, that will probably find new and novel applications in the field of microwave components and antennas for the millimeter wave band.

Keywords Microwave characterization · Dielectric permittivity · Tangent loss

1 Introduction

Millimeter wave electronic have traditionally been associated with specific applications, as science research, defense, or space communications. Nowadays, these technologies are growing into commercial applications for mass market. Current areas of development are the automotive radars at 77 to 90 GHz, the 60-GHz low-range communication networks, millimeter wave imaging systems, and development of 5G telecommunication systems based on MIMO in the millimeter wave bands. Here, we refer the reader to good reviews on these technologies as [1–4]. A fundamental step for these high impact applications is the use of

✉ Nicolás Reyes
nireyes@uchile.cl

¹ Department of Electrical Engineering, Universidad de Chile, Tupper, 2007 Santiago, Chile

² Department of Astronomy, Universidad de Chile, Camino el observatorio, 1515 Santiago, Chile

novel technologies, but also issues as weight, power consumption, fabrication costs, reproducibility, etc., are drivers as important as the final component performance. To achieve these goals, the use of standard fabrication process is important. Synthetic organic polymers, or plastic materials, are one of the most versatile materials in the manufacturing industry. They are frequently used in the electronic industry due to their excellent insulation and mechanical properties, and they will certainly find applications in the mm-wave components and systems industry. In this paper, we provide experimental data for the complex dielectric permittivity of a wide variety of such materials. We focus our measurements in the Q-band (30–50 GHz or 10 to 6-mm wavelength) as it is a representative frequency range of mm-wave regime. We used the filled waveguide method to characterize samples of the following materials: polyamide (PA6, PA66, PA6-C), polyethylene (PE, HDPE, treated HDPE), polytetrafluoroethylene (PTFE), polyoxymethylene (POM), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), phenol formaldehyde resin, polypropylene (PP), polyvinyl chloride (PVC), polyphenylene sulfide (PPS), and polyether ether ketone (PEEK). Previous reports present data for some of these materials [5, 6], but the available data are generally measured at other frequency ranges. Specific materials as polyamides, polyethylenes, and polytetrafluoroethylene have already been studied and are well documented in the literature [7–9], and represent a good comparison point for our set of measurements. Other materials as PLA and ABS are interesting due to their extensive use in the 3D Printing industry but the literature lacks of good measured data at this frequency ranges. Most of previous studies at higher frequencies have been performed using free-space techniques. At mm-wave regime, this approach presents several problems as it requires large and thin samples to avoid diffraction in the borders and standing waves inside the material. The distance between the sample and the measuring antennas is also important as measurement precision can be affected by reflections between the sample and the antennas. Classical approaches using filled waveguides also use thin samples, as simple algorithms have the problem of increasing estimation uncertainty as the width of the sample gets too close to multiples of half the wavelength. This study overcomes this problem by preparing long samples of each material, where many standing wave maxima and minima are present along the frequency range, and considering not only single frequencies, but the whole interval to compute the permittivity.

2 Experimental Method

The experimental set-up considers a rectangular waveguide completely filled with a sample of the material under test. Samples are machined in a high precision CNC to achieve a good surface quality and to avoid air gaps between the waveguide walls and the sample under test. The waveguide assembly is produced as a split block with the split at the zero current plane. Plastic samples are inserted inside the waveguide assembly prior to each measurement. Despite using the same process, different plastics show different surface qualities due to their inherent different mechanical properties; a final manual polishing was required to uniform the final surface quality of the samples. The scattering parameters of the filled waveguide are measured using a 50-GHz Vector Network Analyzer (VNA) as shown in Fig. 1. A couple of 2.4-mm coaxial to WR22 waveguide adapters are used between the VNA connector and the waveguide assembly. The effect of adapters and cables is removed by the standard 2-port SOLT calibration procedure. As a result, the measured scattering parameters correspond to the reflection

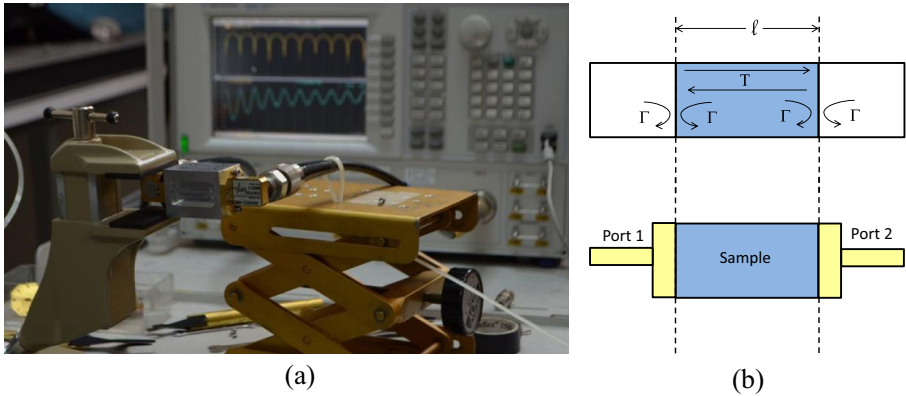


Fig. 1 Experimental system for measurements of dielectric constant of materials. **a** Photography of the measurement system showing the vector network analyzer and the test fixture used for measurements. **b** Presents a conceptual scheme of the measurement system modeled as a partially filled waveguide with a sample of length l . The reference plane is located at the interface between material and air filled waveguide. Using the analyzer the reflection (Γ) and transmission (T) coefficients are obtained

and transmission at the interfaces between our material and the air filled waveguide, as shown in Fig. 1b. At this frequency range, it is important to have in mind that VNA cables can induce phase errors if they are twisted or moved after the calibration procedure. Our setup reduces these effects by having one of the ports mechanically fixed to the test bench and a system that minimizes bending during successive connection and disconnections of the samples.

2.1 Permittivity Estimation

The system can be modeled as a couple of air filled rectangular waveguides that interface with a central section of waveguide filled with the material under test, as represented in Fig. 1b. The measured S-parameters are related with the complex dielectric permittivity by Eqs. (1)–(6). The effect of multiple reflections inside the sample in the measured scattering parameters is presented in Eqs. (1) and (2).

$$S_{11} = S_{22} = \frac{\Gamma(1-T^2)}{1-\Gamma^2T^2} \tag{1}$$

$$S_{21} = S_{12} = \frac{T(1-\Gamma^2)}{1-\Gamma^2T^2} \tag{2}$$

where Γ represents the reflection coefficient at the interface between the filled waveguide and the air filled waveguide. T represents the transmission coefficients between the two ends of the sample. Both coefficients are related to the waveguide propagation constants as presented in Eqs. (3) and (4).

$$\Gamma = \frac{\gamma_0 - \gamma}{\gamma_0 + \gamma} \tag{3}$$

$$T = e^{-\gamma l} \quad (4)$$

Each waveguide is characterized by its own propagation constant, γ for the filled waveguide, and γ_0 for the air filled waveguide.

$$\gamma = \sqrt{\kappa_c^2 - \epsilon_r \kappa_0^2} \quad (5)$$

$$\gamma_0 = \sqrt{\kappa_c^2 - \epsilon_0 \kappa_0^2} \quad (6)$$

where κ_0 is the wave number in free-space ($\kappa_0 = \omega \sqrt{\epsilon_0 \mu_0}$), and κ_c represents the cut-off wave number of the TE₀₁ mode, which for a rectangular waveguide becomes $\kappa_c = \pi/a$ with a being the width of the waveguide. It is reasonable to assume a relative permeability of the sample equal to 1 ($\mu_0 = 1$). Finally, $\epsilon_r = \epsilon_r' + j \epsilon_r''$ is the complex relative permittivity of the material. We present here the complex part of the dielectric constant as the tangent loss, which is computed as (7),

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} \quad (7)$$

Two of the most common methods to compute the complex permittivity are the Nicolson-Ross-Weir (NRW) [10] and the NIST Non-Iterative [11], which achieve good results when the length of the sample is not close to multiples of half the wavelength of interest. However, the computing power has increased to a point where more sophisticated error-minimization algorithms can be used to estimate the permittivity value. This is the method used in the paper, where the algorithm finds the best ϵ_r that minimizes the mean squared-error between the measured S-parameters and the model described by the Eqs. (1)–(6). It is assumed that dielectric permittivity has no significant variation over the limited frequency range of this study, allowing the algorithm to estimate a global-average permittivity using all the available data, minimizing uncertainty. However, the analysis can be also performed over a specific frequency interval if required. Figure 2 presents an example of the measurements of the reflections and transmissions and the results of the model described previously for a waveguide filled with PTFE.

3 Results

Table 1 shows the obtained results for our samples. For each material family, we tested several samples from different providers, and with different features as color, production system or commercial name. Over the complete band and in all the samples measured, the error in the estimation of ϵ_r' and $\tan \delta$ was below 0.5% and 3% respectively. The measured complex relative permittivity is expressed as the real part ϵ_r' of the dielectric constant and the tangent loss of the material. In the same table, we present values previously reported in the literature to easily compare our results with previous reported or non-existing data. Furthermore, for the material: ABS, PA, HDPE, and PP, our results are in accordance with the values of the refractive index and absorption coefficient presented at higher frequencies (above 200GHz) in reference [12].

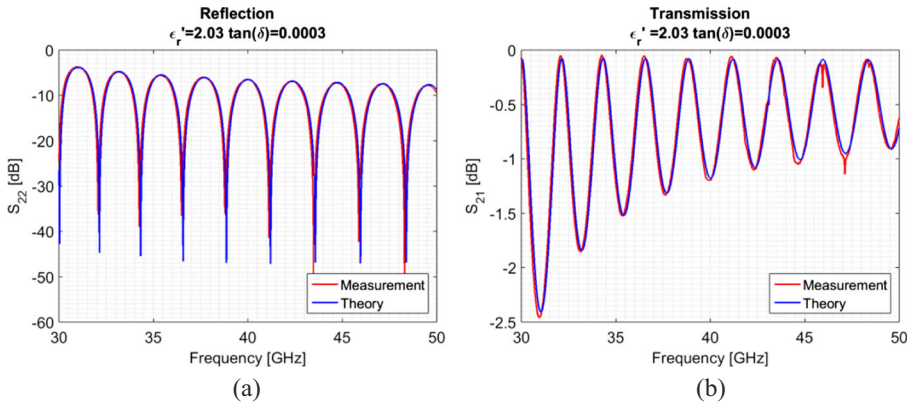


Fig. 2 Experimental and modeled response of the filled waveguide system. The vector analyzer measures the scattering parameters of the sample. **a** The reflected power across the frequency range and corresponds to the measured scattering parameter S_{11} . **b** The transmitted power across the frequency range and corresponds to the measured parameter S_{21} . Data are presented in logarithmic scale (dB)

The first presented material is PTFE or teflon, a widely used material for microwave components, that has $\epsilon_r' = 2.0$ and a relatively small tangent loss of $3.0 \text{ E-}4$. Our measurements are coincident with previous data and this measurement was used as a comparative point to other reports in the literature. Polyamides are widely used as synthetic fibers in the textile industry. They are also used as engineering plastic. The most common material in this family is nylon. We measured four samples from different providers of nylon. Sample 1 corresponds to PA6, sample 2 is a MC901 PA6, sample 3 is a PA66, and sample 4 is a PA6 with addition of molybdenum disulfide. They have similar dielectric constant values around $\epsilon_r' = 3.1$ and a high tangent loss of approximately $1.0\text{E-}2$. Different samples of polyethylene have little differences on their absolute permittivity values, but relatively large variations in the tangent loss values. Samples 1 and 2 correspond to blue and green High Molecular Weight (HWM) PE respectively. For HMW PE, we found that little differences, as the presence of colorants in otherwise identical materials have an appreciable impact on the value of tangent losses. Comparable values for ϵ_r' and tangent losses are obtained for samples 3 and 4, which corresponds to white and yellow ultra high molecular weight (UHMW) PE respectively. Sample 5 corresponds to high-density polyethylene (HDPE). The results from samples 3 and 5 show that no large variation in ϵ_r' is appreciated along with different molecular weights of the materials. The obtained values are similar to previously reported values. Polylactic acid is widely used in additive manufacturing processes. We measure three samples: sample 1 was produced in 3D printing machine, samples 2 and 3 corresponds to light blue and dark blue respectively. They exhibit a tangent loss of the order of $1.0\text{E-}2$, and a ϵ_r' in the range of 2.6 to 2.8. The acrylonitrile butadiene styrene or ABS is a strong and resistant plastic that is widely used in the electronic industry. The sample was produced using 3D printing technology. The real part of the measured dielectric constant ϵ_r' is 2.4 with a tangent loss of $5.5 \text{ E-}3$, almost half of the losses measured for PLA. POM is a thermoplastic material with excellent mechanical properties. It is used for parts that require high dimensional stability, resistance, and rigidity. Our measurements of two samples from different providers show a tangent loss in the range of $7.0\text{E-}3$ to $1.8\text{E-}2$ and a dielectric constant between 2.8 and 3.0. We measured just one sample of polypropylene, a well-known low loss material used in radomes and infrared filters along the mm-wave band.

Table 1 Summary of reported permittivity values for plastic materials. We also present for comparison previous published values. Relevant references are [6–9]

Family	ID	Description	Permittivity (ϵ_r')		Tangent loss ($\tan \delta$)		Reference
			This work	Ref	This work	Ref	
PTFE	1		2.03	1.75–2.10	3.0 E-4	2.0–6.0 E-4	[6–9]
Polyamide	1	PA6	3.06	3.20	1.1 E-2	8.5 E-3	[6]
	2	MC 901 PA6	3.05		1.0 E-2		
	3	PA66	3.06		1.2 E-2		
	4	PA6+ MoS ₂	3.01		1.0 E-2		
Polyethylene	1	Blue HMW	2.32	2.29–2.34	6.0 E-4	2.0–5.0 E-4	[6, 7]
	2	Green HMW	2.32		2.0 E-4		
	3	White UHMW	2.30		9.0 E-4		
	4	Yellow UHMW	2.36		11.0 E-4		
	5	HDPE	2.34		2.0 E-4		
Polylactic acid	1	Yellow, 3D print	2.57		9.5 E-3		
	2	Light blue	2.72		10.0 E-3		
	3	Dark blue	2.71		10.0 E-3		
ABS	1		2.40		5.5 E-3		
POM	1	Ertacetal ®	2.79		1.8 E-2		
Polypropylene	1		2.27	2.17–2.25	7.0 E-4	1.0–7.5 E-4	[6, 7, 9]
PVC	1		2.83		7.6 E-3		
	2		3.58		6.6 E-2		
Phenol resin	1	Durocoton (*)	3.58		6.6 E-2		
	2	Celisol (*)	3.73		5.7 E-2		
PEEK	1	Ertapeek (*)	3.12		4.4 E-3		
PPS	1	Ultraxcel (*)	3.09		4.1 E-3		

(*) Commercial name used by Plastigen S.A., Camino lo Boza 370, Pudahuel Chile

Our measurement indicates a tangent loss in the range of 7.0 E-4 and $\epsilon_r' = 2.3$. PVC is one of the most common polymers used in the industry for many applications. The real part of the measured permittivity is 2.8 and the tangent loss is in the order

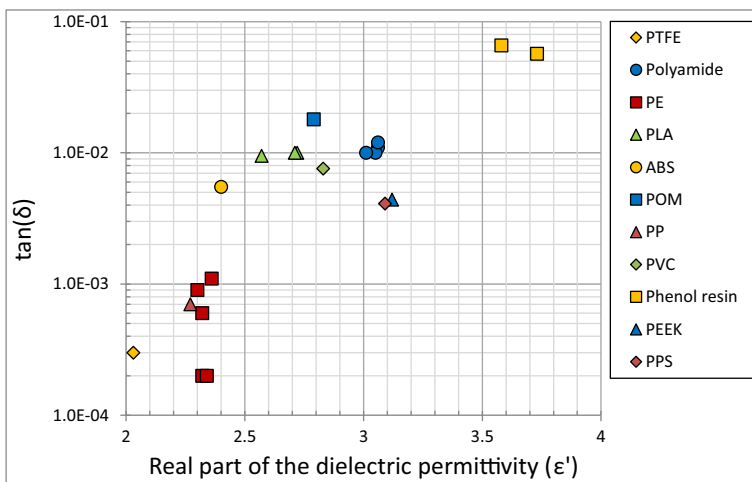


Fig. 3 Summary of results showing the real part of the measured dielectric permittivity and tangent losses of different materials. Different colors and symbols correspond to different materials and allow us to observe the dispersion of ϵ_r' and $\tan \delta$ for a specific material

of 7.5×10^{-3} . Phenol resin compound presents the highest permittivity of all the tested materials but also the higher tangent loss. The difference between different samples is noticeable. Polyether ether ketone or PEEK is an advanced engineering plastic material. Its robustness makes it suitable for demanding applications; it is also considered an advanced biomaterial for implants. Other advanced plastic material is the Polyphenylene sulfide or PPS. This material is used in chemical aggressive ambient as no acid or alkaline compound attacks it. The material is interesting as precursor for electrical conducting plastic materials. Both PEEK and PPS present similar results. They have a relatively high dielectric constant of 3.1 and a low tangent loss of the order of 4.0×10^{-3} .

4 Conclusions

We have presented a comprehensive set of data for complex dielectric permeability of different thermoplastic compounds. Measurements were performed in the Q-band, corresponding to 30–50 GHz, providing valuable information for component designers working in the millimeter wave bands. Table 1 and Fig. 3 present a complete overview of the performed material characterizations.

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