Terahertz Dielectric Characterization of Low-Loss Thermoplastics for 6G Applications

Min Zhai, Alexandre Locquet, D. Citrin

Terahertz dielectric characterization of low-loss thermoplastics for 6G applications

Min Zhai [1,2] · Alexandre Locquet [1,2] · D.S. Citrin [1,2]

Abstract Common thermoplastics, *namely*, polycarbonate (PC), poly (methyl methacrylate) (PMMA), and acrylonitrile butadiene styrene (ABS) are low-cost materials with potential applications in emerging 6G communications systems, ranging from microelectronics packaging to metasurfaces for reflectors and filters. In addition, low-loss materials are also needed for more pedestrian applications, such as packaging for entire handheld devices, subassemblies, and high-frequency windows where low-cost is key and long lifetime might not be a requirement. In this work, we utilize terahertz time-domain spectroscopy from 500 GHz to 2 THz to characterize the dielectric properties and loss tangent for each thermoplastic above. The plastics investigated have refractive index (∼1.6–1.7) in the 6G band with low dispersion. The absorption, however, increases at high frequencies as is common in disordered materials, highlighting a key challenge for 6G. Nonetheless, in absolute terms, all the thermoplastics studied present low-loss performance compared with (higher–index) common glasses and ceramics within the entire frequency range, suggesting that they are promising candidates for selected applications for future 6G systems.

Keywords Terahertz spectroscopy · Material characterization · Thermoplastic · Dielectric constant · Loss tangent.

D.S. Citrin
david.citrin@ece.gatech.edu

[1] Georgia Tech-CNRS IRL2958, Georgia Tech Lorraine, 2 Rue Marconi, 57070 Metz France,

[2] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

1 Introduction

Great effort is underway to deploy commercial 5G–and to develop future 6G–networks. The 5G spectrum is limited above by 100 GHz; however, 6G extends the upper frequency to 3 THz. Applications such as ar- tificial reality (AR), real-time super-resolution imag- ing, autonomous driving, smart city, and the internetof things will benefit from 5G deployment, but moreso from 6G systems. At every level, choices will need to be made concerning materials–from the device level to microelectronics packaging to handheld device packaging to building metasurfaces for reflectors and filters. Glasses, ceramics, and semiconductors have been investigated for high-index terahertz (THz) materials [1–3]; however, with high index typically comes high losses for disordered materials. For waveguides and transmission lines, high-index media may be desirable. Low refractive index, though, is also of interest to enhance radiation efficiencies that are otherwise suppressed due to substrate coupling [4]. Our focus here is on selected low-cost and common plastics for their low-loss/low-index properties in the 6G band for microelectronics packaging and other high frequency applications.

Thermoplastics provide a wide range of materials choice. The THz dielectric properties of several polymers have been investigated previously [5–15], For example, PTFE is often used for THz lenses and win- dows [6, 10]. Our focus here is on three common and inexpensive plastics, *namely*, polycarbonate (PC), poly (methyl methacrylate) (PMMA), and acrylonitrile butadiene styrene (ABS), though many other materials are readily available. Despite past THz characterization of plastics, there are not many measurements in the literature on these specfic materials covering the same frequency band. Moreover, some of the measurements are up to two decades old, while the sample-to-sample variability of many plastics calls for more measurements. These materials are of interest not necessarily for microelectronics packaging, but for packaging of entire handheld devices or systems or providing low-cost windows to enable high transmission of signals. When it comes to various applications, other considerations will also come into play, including moisture absorption, poor thermal conductivity, and poor thermal and chemical stability of many plastics. In addition, ultrasmooth surfaces may not be readily attainable. Still, plastics remain attractive choices for situations where low cost is important and exposure to demanding environments may not be an issue. In other words, ultimately, materials choices for deployment in the field will require tradeoffs.

The literature related to the THz dielectric properties of materials is vast but scattered. The specific 6G context in this regard, however, has attracted limited attention, while much of the discussion that does exist concentrates on microelectronic packaging with little consideration of applications related to packaging entire handheld devices or subassemblies. In Refs. [16–18], polymer films were laminated on both sides of glass substrate to explore the use of this stackup as a microelectronics substrate and to fabricate waveguides and transmission lines. Loss tangent tan $\delta \approx 0.01$ were measured in the 50–140 GHz range, barely touching the 6G band. Such structures are of interest for microelectronic packaging applications for 5G, and likely for 6G. It is important to note, however, that the the dielectric properties of materials in the THz regime are quite different from DC, microwave, and optical-frequency values, necessitating actual THz measurements.

Mass-produced thermoplastics vary widely insofar as polymer-chain length, chemical purity, degree of crystallization, density, degree of preferential molecular orientation, incorporation of frozen-in stress, and tacticity (for certain polymers). Surface texture also affects measured losses and varies widely depending on manufacturing conditions and surface treatment. It is not our aim here to provide precise values for ultrahigh purity materials prepared under controlled conditions, but to give representative values for off-the-shelf materials. As mentioned above, for applications such as packaging of entire handheld devices or subassemblies and windows, low cost and no requirement for long lifetime may drive interest in these plastics.

This paper presents a systematic characterizationof the dielectric properties of three frequently used, low-cost, and off-the-shelf thermoplastics using a commercial THz time-domain spectroscopy (TDS) system over a broad frequency ν range from 0.5 to 2 THz.The frequency-dependent refractive index $n(\nu)$, attenuation coefficient $\alpha(\nu)$, complex permittivity $\varepsilon(\nu)$, and loss tangent tan $\delta(\nu)$ of PC, PMMA, and ABS are presented. These characterized materials present low refractive index (compared with glass and many crystalline materials) and low loss.

2 Method: Experimental setup and signal processing

The transmission measurements in this work were performed using a commercial pulsed broadband THz time-domain spectroscopy (TDS) system (TPS Spectra 3000 from TeraView Ltd.). Compared to vector network analyzers (VNA), another instrument employed in Ref. [18] to measure the dielectric properties of materials in the 5G band, the higher frequency resolution thus enabled, is of little interest due to the rather featureless nature of $\varepsilon(\nu)$ in the THz band [1, 19]. The system produces quasi-single-cycle THz pulses at a repetition rate of 100 MHz. The detection is capable of mapping out the amplitude of the THz electric field in time subsequent to propagation through the plastic sample. The effective bandwidth of THz pulses generated by our THz system is from 60 GHz to 3 THz. Because of the low signal- to-noise ratio (SNR) after interacting with the sampleat the extreme ends of this band, however, only $\nu \in$ [0.5 THz, 2 THz] is used for the analysis. Note that we measure the full time-dependent electric field of THz signals, *i.e.*, we obtain full amplitude *and* phase information. A flow of dry N_2 was introduced into the propagation path during the measurements to suppress atmospheric water-vapor absorption. The spectral range for this setup is [$\sim$60 GHz, $\sim$3 THz] and 1800 scans were collected and averaged to eliminate random amplitude fluctuations in the femtosecond mode-locked laser and photoconductive THz source. Balancing the noise level in the spectrum as well as the spectral resolution, a Black-Harris 3-term apodization was utilized to suppress apparent noise in the spectrum.

The frequency-dependent refractive index $n(\nu)$ and attenuation coefficient $\alpha(\nu)$ of the plastics are obtained from the measured time-dependent electric field after Fourier transforming the time-domain signal (electric field) transmitted through the sample and through air (reference signal), with electric-field amplitude and phase $E_s(\nu)$, $\phi_s(\nu)$ and $E_r(\nu)$, $\phi_r(\nu)$, respectively [20],

$$\alpha(\nu) = -2/d \ln[E_s(\nu)/(T(\nu)E_r(\nu))], \quad (1)$$

$$n(\nu) = 1 + c[\phi_s(\nu) - \phi_r(\nu)]/(2\pi\nu d). \quad (2)$$

where d is the sample thickness and $T(\nu)$ is the transmittance associated with the air/plastic and plastic/air interfaces,

$$T(\nu) = 4n(\nu)/[n(\nu) + 1]^2. \quad (3)$$

Furthermore, the complex permittivity $\varepsilon(\nu) = \varepsilon' + i\varepsilon'$ and loss tangent $\tan\delta(\nu)$ are related to $n(\nu)$ and $\alpha(\nu)$ by

$$\varepsilon' = n^2 - k^2, \quad (4)$$

$$\varepsilon'' = 2nk, \quad (5)$$

$$\tan\delta = \varepsilon''/\varepsilon', \quad (6)$$

where k is the extinction coefficient (imaginary part of the complex refractive indices $n + ik$), $k = \alpha\lambda_0/(4\pi)$ with $\lambda_0 = c/\nu$ the wavelength *in vacuo* and c the speed of light.

3 Results: THz spectroscopy and thermoplastics

Three commercial thermoplastics, *viz.* PC, PMMA, and ABS, are studied in this present work, with relevant material properties given in Refs. [21, 22] (in which cer- tain similar THz measurements were also made). Since the surfaces of all samples are visibly smooth and flat, surface scattering is not expected to be significant for our study near normal incidence (though is expected to be an issue for propagation in the plane of the plastic sheets).

From Eqs. (1) and (2), $n(\nu)$ and $\alpha(\nu)$ were obtained directly from the experimental measurements of the THz signals and are presented in Fig. 1. PMMA ex- hibits a somewhat lower $n(\nu)$ than the other plastics. In all cases, $n(\nu)$ exhibits a slightly negative dispersion $dn/d\nu$ with $n(\nu)$ for PMMA reducing from 1.63 at 0.5 THz to 1.59 at 2 THz, for PC reducing from 1.67 at 0.5 THz to 1.64 at 2 THz, and for ABS reducing from 1.68 at 0.5 THz to 1.64 at 2 THz. This trend is con- sistent with previous reports for similar materials inRefs. [7, 23] though as pointed out *supra*, values of the optical constants vary in the literature.

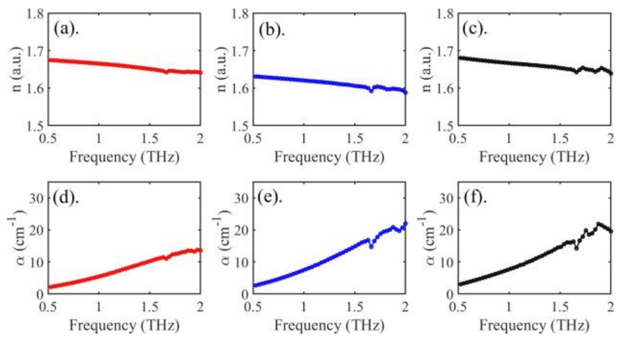

Fig. 1 $n(\nu)$ for (a) PC, (b) PMMA, and (c) ABS, $\alpha(\nu)$ for (d) PC, (e) PMMA, and (f) ABS, from 0.5 THz to 2 THz.

Figure. 1(b) shows $\alpha(\nu)$, with α(0.5 THz) for PMMA, PC, and ABS is 2.5 cm^{-1}, 2.1 cm^{-1}, and 2.9 cm^{-1}, re- spectively, with α(2 THz) increasing to 22 cm^{-1}, 13.6 cm^{-1}, and 19.6 cm^{-1}. The feature at ∼1.66 THz is likely due to a water-vapor resonance [24]. The values of $\alpha(\nu)$ obtained in this work are consistent with the literature [7, 23, 25]. For example, in Ref. [23], for PC n(1 THz)= 1.665 and α(1 THz)= 9.6 cm^{-1}, while for PMMA n(1 THz)= 1.61 and α(1 THz)= 11.3 cm^{-1},
though the losses we measure at 1 THz are somewhat lower. Note that earlier work [7, 26, 27] (also cited in Ref. [23]), while finding similar values for refractive in- dex for PC and PMMA, shows large scatter in the loss measurements for PMMA.

Since the 1970's, it has been noted that at low fre- quencies, $\alpha(\nu)$ for materials with disorder varies with ν as a power law [28, 29]. A refinement of the ideas presented followed the observation that the product $n(\nu)\alpha(\nu)$ for amorphous materials obeys a power-law relation [13, 25, 30]

$$n(\nu)\alpha(\nu) = K(h\nu)^{\beta} \quad (7)$$

where h is the Planck constant, and absorption param- eter K is a material-dependent [30]. The exponent β is related to the characteristics of the disorder, and satisfies $\beta \leq 2$. For glasses, typically $\beta \approx 2$; however, for plastics in many cases, β is somewhat less than 2. The values of Kh^2 and β are obtained after fitting to $n(\nu)\alpha(\nu)$, and are listed in Table 1. The values of β and Kh^2 obtained by fitting to our data are in close agreement with those quoted in Ref. [11].

Table 1 THz refractive indices $n(\nu)$, Kh^2, and β based on fit to data.

Material	n (a.u.) (average)	Dispersion ($n_{0.5\ THz} - n_{2\ THz}$)	Kh^2 (cm^{-1}s^2)	β
PMMA	1.62	0.04	24.38	1.52
PC	1.66	0.03	23.05	1.37
ABS	1.67	0.04	27.37	1.48

We next convert $n(\nu)$ and $\alpha(\nu)$ to $\varepsilon'(\nu)$ and $\varepsilon''(\nu)$ using Eqs. (4) and (5). Figure 2 shows $\varepsilon'(\nu)$ (left vertical scale). Compared to PC and ABS, PMMA possesses a lower $\varepsilon'(\nu)$ consistent with the lower value of $n(\nu)$ notedabove. In addition, for the three plastics $\varepsilon'(\nu)$ decreases slightly with ν, again, largely reflecting the dispersionin $n(\nu)$. The results here for PMMA can be compared with those of Ref. [15]. Broadly speaking, $\varepsilon'(\nu)$ is in good agreement with their measurements, though we find somewhat higher values of $\tan\delta$ at higher frequen- cies. It should be noted that for loss measurements, there may be a surface-scattering contribution in the measurements both of Ref. [15] and those presented here (and in many other such published measurements). This contribution can be eliminated by comparing measurements on slabs of various thicknesses but with the same surface texture.

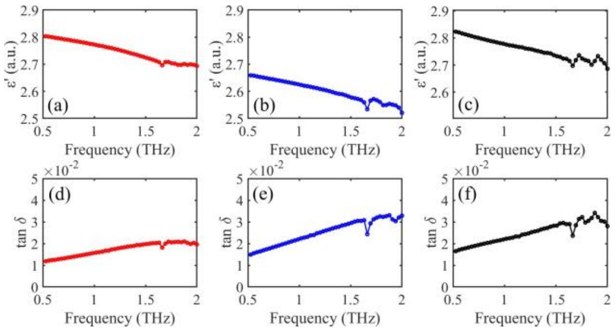

Fig. 2 Measured permittivity $\varepsilon'(\nu)$ for (a) PC, (b) PMMA, and (c) ABS, loss tangent $\tan\delta(\nu)$ for (d) PC, (e) PMMA, and (f) ABS, from 0.5 THz to 2 THz.

Loss tangent $\tan\delta(\nu)$ is determined using Eq. (6). As shown in Fig. 2 (right vertical scale), PC has the lowest tangent consistent with its lower $\alpha(\nu)$ compared with the other plastics. Table 2 summarizes $\varepsilon'(\nu)$ and $\tan\delta(\nu)$ at 500 GHz, 1 THz, 1.5 THz, and 2 THz for the three plastics.

Table 2 Comparision of ε' and $\tan\delta$ between PMMA, PC and ABS.

Material	$\varepsilon'(\nu)$				$\tan\delta$			
	0.5 THz	1 THz	1.5 THz	2 THz	0.5 THz	1 THz	1.5 THz	2 THz
PMMA	2.66	2.63	2.58	2.52	0.015	0.022	0.029	0.033
PC	2.81	2.77	2.72	2.69	0.012	0.016	0.02	0.02
ABS	2.83	2.78	2.73	2.69	0.016	0.022	0.028	0.028

4 Discussion

In this work, the dielectric properties of three common off-the-shelf thermoplastics were characterized using THz time-domain spectroscopy. Refractive index $n(\nu)$, absorption coefficient $\alpha(\nu)$, complex dielectric permittivity $\varepsilon(\nu)$, and loss tangent $\tan\delta(\nu)$ for PC, PMMA, and ABS are presented from 500 GHz to 2 THz. We find that in the entire frequency range, $\tan\delta(\nu)$ varies from 0.012 to 0.033, while $\varepsilon'(\nu)$ is from 2.84 to 3.22. In summary, refractive index and losses are low, for example, compared with glasses. We expect to be some variation in the dielectric properties of each of these materials depending on vendor. While there is overall agreement with past measurements, we must recognize that there is still considerable scatter in some of the data. It should also be pointed out that some of the measurements are up to two decades old calling for reevaluation. There are also not a great deal of data published on ABS.

In all the cases studied, however, low loss together with compatibility with some board-manufacturing processes make these plastics promising candidates for 6G applications, as well as for packaging of modules, systems, and entire hand-held devices and as constituent materials for metasurfaces and other types of filters and reflectors. Photoconductive THz sources integrated with guiding structures and broadside antennae may enable higher optical-to-THz conversion by approaches that incorporate the antenna on a plastic substrate. These materials, while not having long life nor exhibiting favorable thermal properties in many cases, remain attractive for their low cost.

Acknowledgements MZ, AL, and DSC gratefully acknowledge the support of Conseil Régional Grand Est and CPER SusChemProc.

Conflict of interest

The authors declare that they have no conflict of interest.

Data availability statement

The authors will make data available on request.

References

1. M. Ma, Y. Wang, M. Navarro-Cia, F. Liu, F. Zhang, Z. Liu, Y. Li, S. M. Hanham, and Z. Hao, "The dielectric properties of some ceramic substrate materials at terahertz frequencies," *Journal of the European Ceramic Society*, vol. 39, no. 14, pp. 4424–4428, 2019.
2. F. Sanjuan and J. Tocho, "Optical properties of silicon, sapphire, silica and glass in the terahertz range," in *Latin America Optics and Photonics Conference, OSA Technical Digest (Optical Society of America, 2012), paper LT4C.1*, 2012.
3. S. Chen, K. Nguyen, and M. Afsar, "Complex dielec- tric permittivity measurements of glass at millimeterwaves and terahertz frequencies," in *Proceedings of the 36th European Microwave Conference, Manchester, UK*, pp. 384–387, 2006.
4. R. Gharpurey and R. G. Meyer, "Modeling and analysis of substrate coupling in integrated circuits," *IEEE jour- nal of Solid-State circuits*, vol. 31, no. 3, pp. 344–353, 1996.
5. G. Pastorelli, T. Trafela, P. Taday, A. Portieri, L. D, K. Fukunaga, and M. Strlic, "Characterisation of his- toric plastics using terahertz time-doamin spectroscopy and pulsed imaging," *Analytical and Bioanalytical Chem-istry*, vol. 403, pp. 1405–1414, 2012.

6. F. D'Angelo, Z. Mics, M. Bonn, and D. Turchinovich, "Ultra-broadband thz time-domain spectroscopy of common polymers using thz air photonics," *Optics express*, vol. 22, no. 10, pp. 12475–12485, 2014.
7. Y.-S. Jin, G.-J. Kim, and S.-G. Jeon, "Terahertz dielectric properties of polymers," *Journal of the Korean Physical Society*, vol. 49, no. 2, pp. 513–517, 2006.
8. S. Sahin, N. K. Nahar, and K. Sertel, "Dielectric properties of low-loss polymers for mmw and thz applications," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 40, no. 5, pp. 557–573, 2019.
9. A. Podzorov and G. Gallot, "Low-loss polymers for terahertz applications," *Applied Optics*, vol. 47, no. 18, pp. 3254–3257, 2008.
10. M. Naftaly, R. Miles, and P. Greenslade, "Thz transmission in polymer materials–a data library," in *2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics*, pp. 819–820, IEEE, 2007.
11. M. Naftaly and R. E. Miles, "Terahertz time-domain spectroscopy for material characterization," *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1658–1665, 2007.
12. U. Strom, J. Hendrickson, R. Wagner, and P. Taylor, "Disorder-induced far infrared absorption in amorphous materials," *Solid State Communications*, vol. 15, no. 11-12, pp. 1871–1875, 1974.
13. U. Strom and P. Taylor, "Temperature and frequency dependences of the far-infrared and microwave optical absorption in amorphous materials," *Physical Review B*, vol. 16, no. 12, p. 5512, 1977.
14. D. Chen and H. Chen, "A novel low-loss terahertz waveguide: Polymer tube," *Optics Express*, vol. 18, pp. 3762–3767, 2010.
15. T. Chang, X. Zhang, X. Zhang, and C. HL, "Accurate determination of dielectric permittivity of polymers from 75 ghz to 1.6 thz using both s-parameters and transmission spectroscopy," *Applied Optics*, vol. 56, pp. 3287–3292, 2017.
16. J. Tong, Y. Sato, S. Takahashi, N. Imajyo, A. F. Peterson, V. Sundaram, and R. Tummala, "High-frequency characterization of through package vias formed by focused electrical-discharge in thin glass interposers," in *2014 IEEE 64th Electronic Components and Technology Conference (ECTC)*, pp. 2271–2276, IEEE, 2014.
17. W. T. Khan, J. Tong, S. Sitaraman, V. Sundaram, R. Tummala, and J. Papapolymerou, "Characterization of electrical properties of glass and transmission lines on thin glass up to 50 ghz," in *2015 IEEE 65th Elec- tronic Components and Technology Conference (ECTC)*, pp. 2138–2143, IEEE, 2015.
18. M. ur Rehman, S. Ravichandran, A. O. Watanabe, S. Erdogan, and M. Swaminathan, "Characterization of abf/glass/abf substrates for mmwave applications," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 11, no. 3, pp. 384–394, 2021.
19. M. Naftaly, N. Ridler, J. Molloy, N. Shoaib, and D. Stokes, "A comparison method for thz measurements using vna and tds," in *2015 40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, pp. 1–2, IEEE, 2015.
20. N. Palka, M. Szala, and E. Czerwinska, "Characterization of prospective explosive materials using terahertz time-domain spectroscopy," *Applied Optics*, vol. 55, no. 17, pp. 4575–4583, 2016.
21. M. Zhai, A. Locquet, and D. Citrin, "Pulsed thz imaging for thickness characterization of plastic sheets," *NDT & E International*, vol. 116, p. 102338, 2020.
22. M. Zhai, E. T. A. Mohamed, A. Locquet, G. Schneider, R. Kalmar, M. Fendler, N. Declercq, and D. Citrin, "Diagnosis of injection-molded weld lines in abs thermoplastic by polarized terahertz reflective imaging," *NDT & E International*, p. 102497, 2021.
23. E. Fedulova, M. M. Nazarov, A. Angeluts, M. Kitai, V. Sokolov, and A. Shkurinov, "Studying of dielectric properties of polymers in the terahertz frequency range," in *Saratov Fall Meeting 2011: Optical Technologies in Biophysics and Medicine XIII*, vol. 8337, p. 83370I, International Society for Optics and Photonics, 2012.
24. X. Xin, H. Altan, A. Saint, D. Matten, and R. Alfano, "Terahertz absorption spectrum of para and ortho water vapors at different humidities at room temperature," *Journal of Applied Physics*, vol. 100, no. 9, p. 094905, 2006.
25. M. Naftaly and R. Miles, "Terahertz time-domain spectroscopy of silicate glasses and the relationship to material properties," *Journal of Applied Physics*, vol. 102, no. 4, p. 043517, 2007.
26. V. Bershtein and V. Ryzhov, "Far infrared spectroscopy of polymers," in *Polymer analysis and characterization*, pp. 43–121, Springer, 1994.
27. V. Ryzhov, "Low-energy libration excitations in glassy pmma," *Solid State Physics*, vol. 44, pp. 2229–2233, 2002.
28. A. K. Jonscher, "The 'universal'dielectric response," *Nature*, vol. 267, no. 5613, pp. 673–679, 1977.
29. A. K. Jonscher, "The universal dielectric response and its physical significance," *IEEE Transactions on Electrical Insulation*, vol. 27, no. 3, pp. 407–423, 1992.
30. S. Taraskin, S. Simdyankin, S. Elliott, J. Neilson, and T. Lo, "Universal features of terahertz absorption in disordered materials," *Physical Review Letters*, vol. 97, no. 5, p. 055504, 2006.