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Optical Properties of 3D Printable Plastics in the THz Regime and their Application for 3D Printed THz Optics

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Abstract We characterize the terahertz (THz) properties of several materials which can be used for fused material deposition 3D printing. We identify Polystyrene as a material which shows a promising compromise between printability and THz transparency. Furthermore, printed THz lenses are presented and characterized.

1 Introduction

Recently terahertz science and technology has experienced a tremendous progress. Many practical applications are foreseen for THz systems. They range from non-destructive testing [1], and process monitoring in the industry [2, 3] to free-space communications with THz carrier waves [4]. Besides, THz spectrometers are widely used to study different states of matter [5, 6].

Yet, a mature THz technology not only requires sources and detectors but also devices to guide THz waves. This includes lenses [7, 8], reflectors [9, 10], waveguides [11, 12], and splitters [12]. 3D printers hold the potential to inexpensively and efficiently produce such devices.

In this paper we present the THz properties of various polymer materials which can be processed by 3D printers and present two THz lenses fabricated using one of these materials.

During the last years, the price for fused material deposition 3D printers dropped considerably. Those printers extrude melted material and plot the part layer by layer [13]. In principle, any thermoplastic material can be used, but depending on the melting point, thermal expansion coefficient, and elasticity, the printing quality varies considerably. The printing resolution of such devices can be as low as a few microns in depositing direction, while the resolution in the inplane direction is typically not lower than 20μm. Therefore, this technique is perfectly suited for producing small batch series of customized quasi optical components for the terahertz range.

In this paper, we characterize seven different materials which can be used for 3D printing. Five materials are known to be well suited for fused material deposition 3D printing. These are Acrylonitrile butadiene styrene (ABS), Polyactic acid (PLA), Nylon, Bendlay and Polystyrene

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Table 1 Printing parameters of the investigated materials and the material parameters at 500GHz

Material	Printing Temperature [°C]	Sample Thickness [mm]	Refractive Index n @500 GHz	Absorption Coefficient [cm^{-1}] @500 GHz
ABS	250	1	1.57	5
PLA	220	1	1.89	11
Nylon	255	1	1.72	9
Bendlay	250	5	1.532	1.8
Polystyrene	240	5	1.561	0.5
HDPE	230	5	1.532	0
PP	230	5	1.495	0

(HIPS). Additionally, we tried to print with High Density Polyethylene (HDPE) and Polypropylene (PP) which are highly transparent in the THz frequency range, but are non-standard 3D printing materials. For each material we print a cylindrical sample with a diameter of 25 mm and a height of 1 mm and 5mm, respectively. The 1mm thick samples were used for highly absorbing materials like ABS, PLA and Nylon, while the 5mm samples were used for the other materials. All materials were available as 3 mm thick filament which could be directly fed to

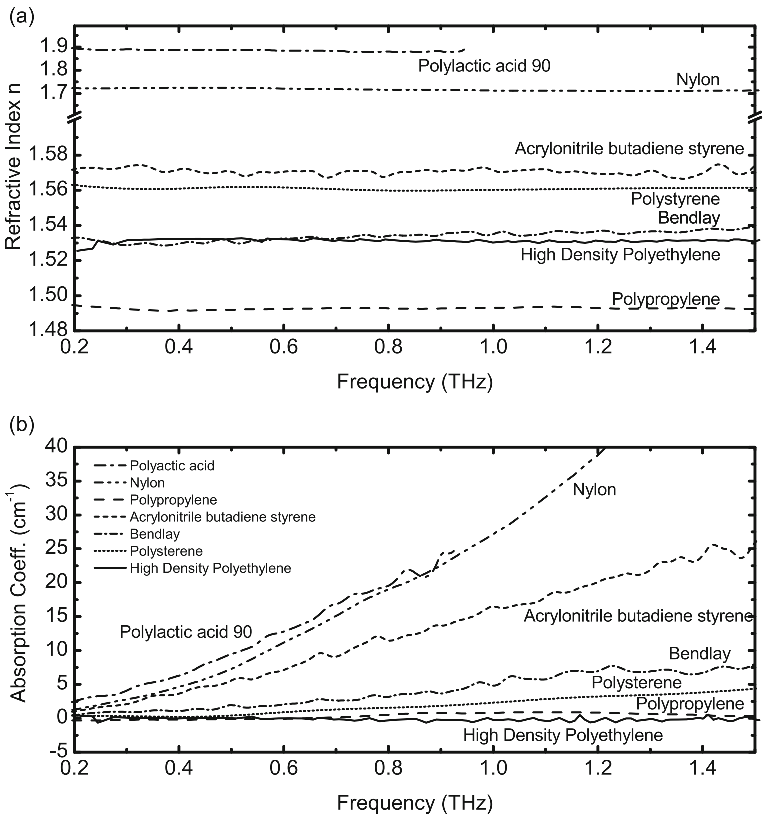

Figure 1 The refractive indices and absorption coefficients of several 3D printable materials

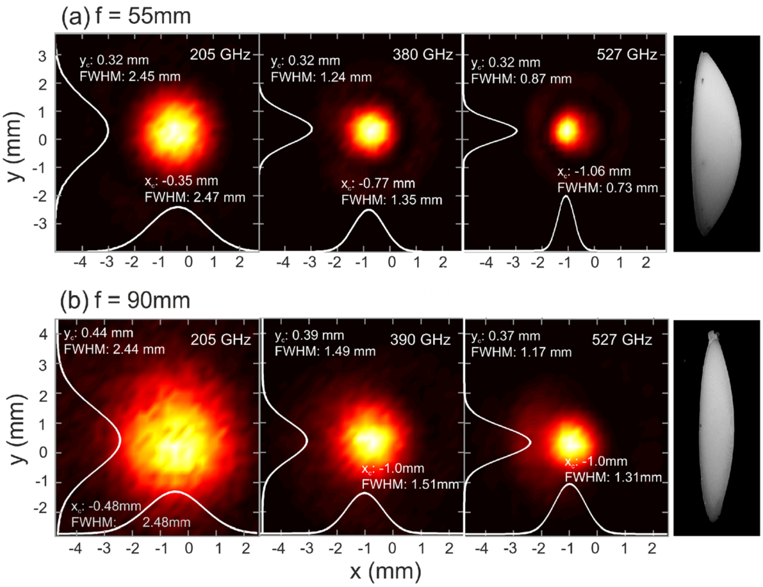

Figure 2 Images of the focal plane at different frequencies for two lenses with focal length of (a) 55mm and (b) 90mm and photographs of the lenses. The white lines indicate the Gaussian fit through the maximum in x- and y-direction. Additionaly, the center of the peak and the full-width at half-maximum is stated.

the 3D printer. We used pure material without additives or coloration and choose the printing temperature as high as possible to prevent internal boundaries which would lead to scattering (see Table 1 for details). Additionally, the printing direction of the samples was altered by 90° for each layer to increase the mechanical strength of the sample.

The measurements were done with a standard free-space Ti:Sapphire laser driven THz spectrometer under nitrogen atmosphere. A pair of photoconductive semi-insulating dipole GaAs antennas emits and detects THz pulses with a bandwidth of 4.5 THz and a signal-to-noise ratio of 60 dB at 400 GHz. For each sample three reference and three sample measurements took place, the resulting measurement data was analyzed using the quasi-space minimization algorithm [14]. Fig. 1(a) shows the refractive indices of the materials. All materials show a flat refractive index profile. The refractive index for most materials is between 1.48 and 1.58. Only Nylon and PLA show higher refractive indices of 1.71 and 1.9, respectively. Yet, the even more important parameter for the use in THz quasi optics is the absorption coefficient, which is plotted in Fig. 1(b). It varies strongly between the different materials. Nearly all materials usually used for 3D printing (PLA, ABS and Nylon) have an absorption coefficient greater than 5 cm^{-1}. Hence, they are too highly absorbing to be used for THz quasi optics. The absorption coefficients of Bendlay and Polystyrene are below 5 cm^{-1} and 2.5cm^{-1} up to 1 THz and below 7.5cm^{-1} and 5cm^{-1} up to 1.5 THz, respectively. The two materials with an almost vanishing absorption coefficient are HDPE and PP. This would make them perfect candidates for 3D printed quasi optics. The absorption coefficient of HDPE appears to be below zero for some frequencies, we address this to the known effect of slight overestimation of the refractive index for a data extraction without Gouy phase correction as described in [15]. Besides the absorption, the printability is an important factor for the material selection. Unfortunately, the printability of HDPE and PP is very poor. Both are very soft materials with a high temperature expansion coefficient and no clearly defined melting point. This makes it extremely hard to print with these materials. Typically, due to internal tension while cooling the sample and the viscosity of previous layers, only small rotation symmetric objects can be printed. Therefore, the best compromise between printability and THz transparency can be achieved by using Polystyrene, especially for quasi optics used at frequencies below 1 THz.

To show the feasibility of the identified material for THz quasi optics, we calculated, fabricated and characterized two plano-convex spherical lenses printed with Polystyrene. Based on the material parameters the lenses were designed using the lens-maker equation (1), for focal length of 55 mm and 90 mm for lens 1 and lens 2, respectively. The resulting lenses had an open aperture of 48mm and were 5 mm and 10 mm thick. The resulting radii of curvature are R =98mm and R =166mm.

$$\frac{1}{f} = (n-1)\cdot\left(\frac{1}{R_2} - \frac{1}{R_1} + \frac{(n-1)\cdot d}{n\cdot R_1\cdot R_2}\right) \tag{1}$$

Each layer was printed in spiral shape, with a layer height of 100 μm. Using a setup similar to the one described in [7], the focal plane of the lenses was imaged. To increase the imaging resolution, a small aperture with a diameter of 400 μm limits the input of the fiber coupled antenna module. The antenna was carefully adjusted in the center of the collimated beam. After that, the lens was placed in the THz beam and slightly adjusted in x- and y-direction until the peak-to-peak signal was maximized again. Additionally, a slight varying of the lens in z-direction ensured that the THz antenna was in the focal plane of the lens. To characterize the beam profile an area 8x8mm^2 around the focal point was raster-scanned with 250μm step size. Fig. 2 shows the results for the two lenses at different frequencies. Additionally, the frequency dependent beam diameter of the illuminating beam was imaged and the frequency dependent FWHM was extracted. Table 2 summarizes the focusing properties of the lenses and compares them with the theoretical excepted beam diameters calculated with Gaussian beam propagation based on the beam sizes of the collimated beams. Both lenses focusing properties are as expected and show spot sizes which are close to the diffraction limit.

In summary we have presented the optical properties for several 3D printable materials at THz frequencies and find that common 3D printing materials are highly absorbing in the THz range. On the other side, materials like HDPE and PP which are highly transparent in the THz region cannot be printed satisfactory. A good compromise between printability and functionality at least for the frequency range below 1 THz is the material Polystyrene.

Table 2 The measured beam diameter of the collimated and focused beam for four selected frequencies is shown. For each lens and frequency, the theoretical beam diameter was determined with Gaussian beam propagation based on the size of the collimated beam.

[mm] (x/y)	205 GHz	380 GHz	527 GHz
Collimated Beam	37 / 33	21 / 23	17 / 18
Lens 1(f=55 mm)			
Measured FWHM	2.47 / 2.45	1.35 / 1.24	0.73 / 0.87
Theoretical FWHM	0.97 / 1.06	0.91 / 0.83	0.81 / 0.76
Lens 2 (f=90 mm)			
Measured FWHM	2.44 / 2.48	1.49 / 1.51	1.31 / 1.17
Theoretical FWHM	1.59 / 1.73	1.49 / 1.36	1.32 / 1.25

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