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Innovative Approaches to Fabricate Terahertz Optics with Additive Manufacturing: Manufacture and THz Characterisation of a Silica-Filled Photopolymer

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Abstract

Due to the increasing demand for terahertz optics in medical imaging, communication and spectroscopy systems, research into using Additive Manufacturing (AM) to manufacture THz optics is rapidly expanding. However, conventional AM feedstock materials are often absorptive in the THz band, with the absorption coefficient of commercially available photopolymers ranging from 19 – 25 cm^{-1} at 1 THz making them unsuitable for low-loss THz applications, such as refractive THz lenses and waveguides.

Literature had shown silica to be highly transparent in the THz region, therefore a silica-filled photopolymer sample was manufactured using stereolithography and then characterised from 1 – 4 THz using terahertz time-domain spectroscopy.

The results were promising, with the composite having a lower absorption coefficient (10.71 cm^{-1}) and a higher refractive index (1.72) at 1 THz than standard photopolymers. This work demonstrates that AM-produced ceramic-filled photopolymers could offer unique spectral properties in the THz band desirable for THz optics.

Introduction

The terahertz (THz) frequency range, spanning from 0.1 – 10 THz, has properties desirable for numerous applications. THz radiation can penetrate a range of non-polar material including those which are opaque to visible light [1]. Additionally, the radiation is non-ionizing and safe for biological tissues [2]. The high frequency also allows for large bandwidths, with THz waves having data transfer rates ranging from gigabytes to terabytes per second [3]. Due to these desirable properties, THz systems have a wide range of applications including security screening, medical imaging and high-speed communications [4].

A key component of these systems are optical devices also known as quasi-optics, designed to direct and manipulate THz radiation. However, quasi-optical components are often challenging and costly to produce, with the manufacturing process imposing significant material and design limitations [5].

Research has demonstrated that Additive Manufacturing (AM) can be a viable alternative manufacturing method to moulding and micromachining to produce THz components. Examples of THz devices produced using AM include optics, waveguides and filters [6]. AM can offer greater design freedom, being capable of producing complex high-resolution components, from a variety of materials at low cost [7].

However, due to the wavelength scale of THz ranging from 300 – 30   m for 1 – 10 THz respectively, and quasi-optics requiring feature sizes proportional to the target wavelength, THz optics can require feature sizes as low as 10   m [8]. Achieving feature sizes at this scale is not possible with every form of AM, restricting the number of suitable AM processes.

Vat Photopolymerisation technologies can produce minimum feature sizes comparable to the wavelength scale of supra-THz frequencies (above 1 THz) [9]. However, they have a limited material library consisting of photopolymers, which are highly absorptive at THz frequencies. Figure 1. compares the absorption coefficient of photopolymers to conventionally used materials for THz optics at 1 THz. As shown photopolymers have an absorption coefficient between 19 – 25 cm^{-1}, considerably higher than Polytetrafluoroethylene (PTFE), Polymethylpentene (TPX^{TM}), Cyclic Olefin Copolymer (COC) and Silica which are <4 cm^{-1}. Due to their high absorption, photopolymer THz lenses would be significantly less efficient compared to conventionally moulded or machined lenses.

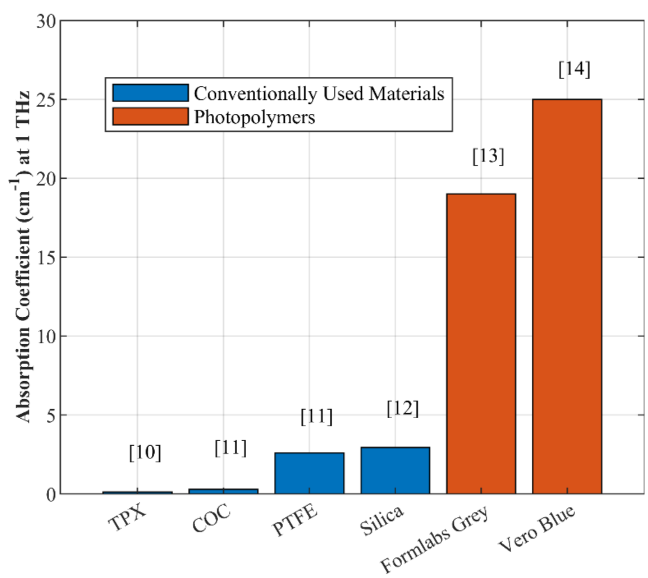

Figure 1. A comparison of the absorption coefficient of conventionally used materials in THz optics and photopolymers at 1 THz. [10–14].

Research has shown that AM composites are a potential solution, with composites having unique spectral properties at THz frequencies. Studies have demonstrated that both the absorption coefficient and refractive index of a polymer can be altered with the addition of filler materials [15]. A recent study found that embedding absorptive iron flakes in a PLA matrix increased the absorption coefficient of the material from 32.6 to 41.6 cm^{-1} and increased the refractive index from 1.54 to 1.70 at 1 THz [16]. The addition of highly transparent filler materials has also been shown to reduce the overall absorption coefficient of composites, introducing a 50% weight ratio of rice husk ash was shown to reduce the absorption coefficient of Acrylonitrile Butadiene Styrene (ABS) from 12.72 to 7.96 cm^{-1} [17].

Therefore, ongoing research aims to identify and characterise composite materials at THz frequencies which are also compatible with high-resolution AM technologies. To discover materials with suitable spectral properties for quasi-optics, potentially allowing for complex, cost-effective THz optics, to be produced using AM.

Methodology

Due to silica being highly transparent in the THz region, with an absorption coefficient around 3 cm^{-1}, a commercially available silica-filled photopolymer was identified as a promising material for THz optics. The manufacturer-supplied material data sheet indicated a silica weight ratio of 55-75%. A literature review revealed that this composite had not undergone prior testing at THz frequencies, with few example studies characterising any AM photopolymers and composites at >1 THz. Therefore, samples of the resin were manufactured to allow for characterisation using a THz time-domain spectroscopy (TDS) system, to determine the spectral properties of the composite.

Fabrication of Silica-Filled Photopolymer Samples for THz Characterisation

Due to the composite resin being a proprietary material for Formlabs printers, the sample design was prepared to be printed on a Form 2 Stereolithography (SLA) printer.

A CAD file was created of a 25 x 25 x 1 mm disk, using Fusion 360. A 25 mm diameter was compatible with existing sample mounts for the THz-TDS system. To characterise the sample above 1 THz relatively thin samples were required to ensure enough THz radiation could transmit through the sample without being absorbed in its entirety to allow a suitable dynamic range across a wide bandwidth to be measured. Therefore, a thickness of 1 mm was chosen, owing to the high absorption coefficient of photopolymers.

PreForm, Formlabs build preparation software was then used to orientate the design and add supports and a raft. The sample was orientated vertically to minimize the amount of support required and to remove the need for supports on critical surfaces required for THz characterisation, see Figure 2. The builds slice data was then exported, sent to the Form 2 and printed.

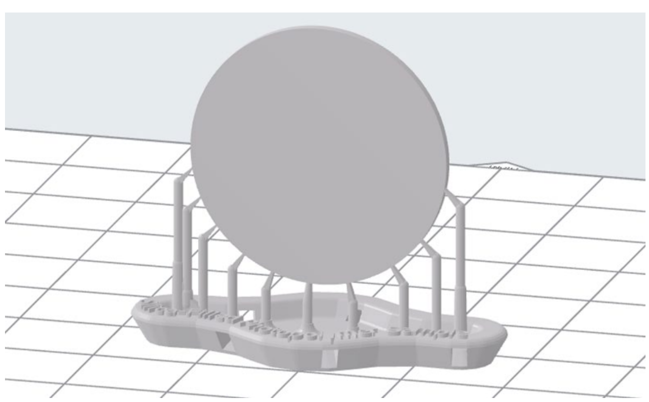

Figure 2. Screenshot of the sample design in the build preparation software (PreForm).

Following printing, samples were cleaned using Isopropyl alcohol (IPA) and post-cured using the FormCure UV curing oven for 60 minutes at 70°C, as recommended by Formlabs.

Fabrication of Standard Photopolymer Samples for THz Characterisation

To allow for direct comparisons, a sample of a commercially available standard photopolymer from Elegoo was also manufactured.

A CAD design of a frame measuring 25 x 25 x 3 mm with a 0.2 mm thick interior recess was produced in Fusion 360. As previously highlighted, due to photopolymers exhibiting high absorption at THz frequencies, THz characterisation >1 THz can prove challenging with thick samples. To resolve this issue a custom design was required. The frame minimized the risk of print failure and ensured that support removal would not damage the delicate 0.2 mm thick structure. Following printing the interior window could be extracted from the frame, which would be compatible with the sample mounts for the TDS system.

As the resin was not a proprietary Formlabs resin and was incompatible with the Form 2, the design was prepared in the build preparation software Chitubox for a Phrozen Sonic 4K Mini Masked Stereolithography (M-SLA) printer. The frame was orientated vertically, with supports and a raft added to the base, see Figure 3. The interior recesses were drafted to remove the need for internal support.

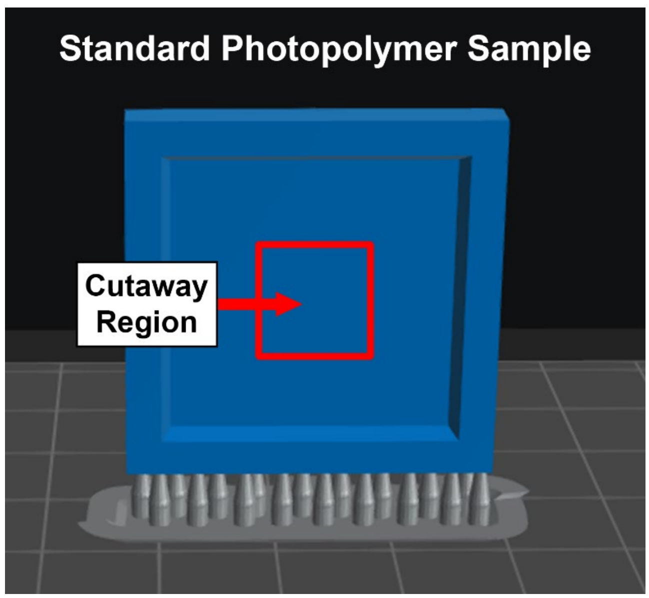

Figure 3. Screenshot of the frame design in the build preparation software (Chitubox).

Unlike PreForm, Chitubox offered greater customisation of the print parameters, requiring the exposure settings. Following the manufacturer's recommendations (Elegoo), the base exposure time was set to 60 seconds with 5 base layers, and the standard layer exposure time was 8 seconds with a 0.05 mm layer height. The builds slice data was then exported and sent to a Phrozen Sonic 4K Mini to print.

Following printing the sample was cleaned using IPA and post-cured using the FormCure. As Elegoo did not provide any post-processing guidance, the sample was cured for 60 minutes. However, no heat was applied to minimize warping.

The standard photopolymer 0.2 mm thick window was then extracted from the sacrificial frame. Images of both samples are shown in Figure 4.

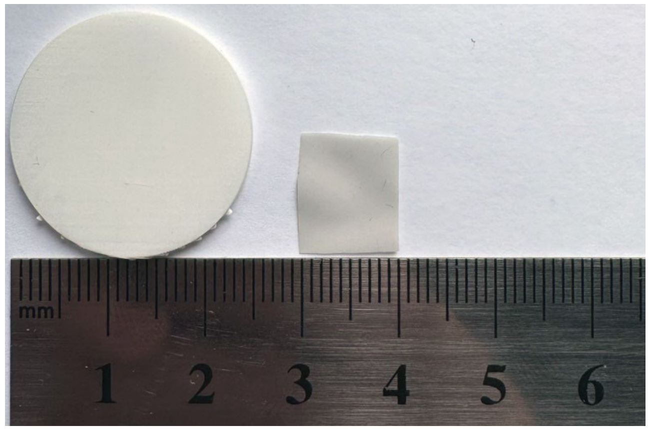

Figure 4. Comparison of the printed silica photopolymer (left) and standard photopolymer (right) samples.

THz Characterisation of 3D-Printed Samples

Both samples were characterised using a broadband THz-TDS system to determine their optical properties at THz frequencies. The apparatus has been described in existing literature [18].

Firstly, a reference scan was taken without the samples in the beams path. Samples were then mounted and placed into the system individually for each scan. While conducting measurements the system was continuously purged with dry air to a relative humidity < 1 % to remove water vapour absorption.

After Fourier transforming the time-domain data the refractive index and absorption coefficient of the samples was determined in the 1 – 4 THz region from the relative changes in phase and amplitude respectively. To assess the suitability of both materials for THz optical applications, the calculation of the absorption coefficient (α) and refractive index (n) was essential. The absorption coefficient relates to the penetration depth of THz radiation before its absorption and the refractive index determines the ability of the material to manipulate THz waves.

Results and Discussion

The absorption coefficient and refractive index of both samples from 1 – 4 THz are presented in Figure 5. As shown, the silica-filled photopolymer had a significantly lower absorption coefficient and higher refractive index than the standard photopolymer.

At 1 THz the absorption coefficient of the silica-filled sample was 10.71 cm^{-1} and raised to around 58.33 cm^{-1} at 4 THz. The silica-filled sample also had a relatively stable refractive index from 1 – 4 THz, ranging from 1.72 at 1 THz to 1.69 at 4 THz.

In comparison the standard photopolymer was highly absorptive with an absorption coefficient of 28.35 cm^{-1} at 1 THz, rising to 113.72 cm^{-1} at 4 THz. The refractive index of the material also decreased from 1.62 at 1 THz to 1.53 at 4 THz.

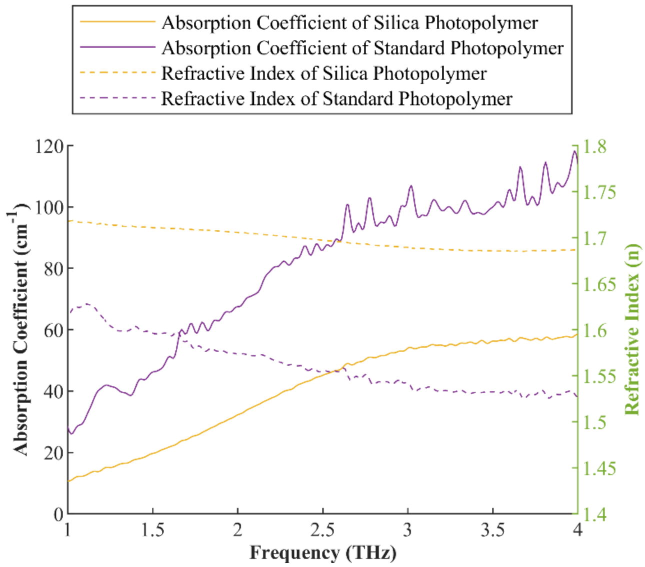

Figure 5. THz-TDS results showing the absorption coefficient and refractive index of silica and standard photopolymer samples (1 – 4 THz). Peaks in absorption are largely due to residual water vapour.

The results indicated that the spectral properties of the composite photopolymer were altered with the addition of silica particles, reducing the absorption coefficient and increasing the refractive index. The silica-filled photopolymer was shown to be a promising material for low-loss THz applications such as refractive THz lenses. With an absorption coefficient 62.2% lower than the standard photopolymer at 1 THz and 48.7% less at 4 THz. The relatively stable refractive index from 1 – 4 THz, 0.03 change over a 3 THz bandwidth, is also desirable for optical devices as the device will function consistently between these frequencies. For example, a refractive THz lens's focal distance will be consistent and require little calibration between 1 – 4 THz.

The spectral properties of the composite could allow for the manufacture of low-cost SLA-produced THz lenses which have greater efficiency and allow for increased manipulation of THz waves. However, the absorption coefficient of the composite was still higher than conventionally used materials in THz optics, such as moulded non-polar polymers which typically have an absorption coefficient <5 cm^{-1} at 1 THz. Future work may involve post-processing the silica-filled photopolymer through debinding and sintering. This may further reduce the absorption coefficient and increase the refractive index of the material, leading to the composite having spectral properties comparable to bulk silica.

Conclusion

To identify highly transparent AM materials at THz frequencies samples of a silica-filled photopolymer and standard photopolymer were printed using stereolithography and masked stereolithography, respectively. Both samples were then characterised up to 4 THz using THz time-domain spectroscopy to determine their spectral properties. The results revealed the silica-filled composite as a promising material with a significantly lower absorption coefficient and higher refractive index than the standard photopolymer at 1 – 4 THz. This work demonstrates that AM composite photopolymers could offer unique spectral properties at THz frequencies desirable for quasi-optical components. Allowing for complex, cost-effective THz optics to be manufactured using low-cost stereolithography systems using commercially available composite photopolymers.

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Data Statement

The data associated with this paper are openly available from the University of Leeds Data Repository. https://doi.org/10.5518/1574

Open Access Statement

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