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Optical Characterisation of Stereolithography-Printed Composites for THz Quasi-Optical Applications

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***Abstract*—High-resolution additive manufacturing (AM) processes can fabricate complex quasi-optical designs with features and smooth surfaces with dimensions comparable to wavelengths in the THz band (0.1–10 THz). However, stereolithography processes are limited by the optical properties of photopolymers, which have absorption coefficients ranging from 19 to 27 cm^{-1} at 1 THz.**

To explore the potential of filler materials for enhancing the THz transparency of photopolymers, standard photopolymer and composite photopolymer samples, including a PTFE-filled (~ 30% PTFE by weight) and a silica-filled (~66% silica by weight) photopolymer were fabricated using a stereolithography printer. The absorption coefficients and refractive indices of samples were then characterised using a terahertz time-domain spectroscopy (THz-TDS) system from 500 GHz to 2 THz.

The results demonstrated that both composite samples exhibited enhanced transparency to THz radiation from 1–2 THz. At 1 THz, the absorption coefficient of the PTFE-filled photopolymer was 15.33 cm^{-1}, which was 27.65 % lower than that of the standard photopolymer, whilst the silica-filled photopolymer had an absorption coefficient of 11.74 cm^{-1}, representing a 44.60 % decrease.

This work demonstrates that filler materials can tailor the optical properties of photopolymers, enabling the fabrication of more efficient stereolithography printed quasi-optical designs.

Keywords – Additive Manufacturing, 3D Printing, THz, Quasi-Optics, Photopolymer Composite

I. INTRODUCTION

Terahertz (THz) radiation, spanning 0.1–10 THz, exhibits unique properties that can support a wide variety of applications. The radiation is non-ionizing and can penetrate a range of non-polar materials [1]. Its high frequency enables large bandwidths, making it promising for high-speed wireless communications. These characteristics allow for applications in security screening, medical imaging, spectroscopy and next-generation wireless networks.

THz systems used in these applications rely on quasi-optical components that direct and manipulate THz radiation. Conventional optics are often molded or machined, making complex designs costly and challenging to manufacture.

Research has demonstrated that additive manufacturing (AM) processes can be used to fabricate complex, low-cost quasi-optical designs from a wide range of materials [2].

However, high-resolution AM technologies are required to produce features and smooth surfaces with dimensions comparable to wavelengths in the THz region (3 mm to 30 μm). Stereolithography (SLA) has been shown to be capable of producing feature sizes below the wavelength scale of 10 THz (30 μm). Additionally, SLA processes can produce surfaces with average roughness values of less than 5 μm [3]. Therefore, these processes are well suited for manufacturing complex quasi-optical designs with minimal attenuation from geometric features.

Despite this, SLA is limited to photopolymer feedstock materials which polymerize when exposed to ultraviolet (UV) light. Photopolymers are absorptive in the THz region, with absorption coefficients ranging from 19–27 cm^{-1} at 1 THz [3]. Therefore, quasi-optical components fabricated from photopolymers would experience high levels of attenuation.

One solution to reduce the absorption coefficient of photopolymers is the incorporation of filler materials, creating photopolymer composites with optimized optical properties. Peng et al, found the addition of 40 % by weight of quartz powder to a photopolymer matrix reduced the absorption coefficient from 21.09 cm^{-1} to 12.18 cm^{-1} at 1 THz [4]. However, this composite was cast and not processed via AM.

Studies have examined the optical properties of ceramic-filled composites, processed via SLA [5], the printed samples typically undergo extensive post-processing, including thermal debinding and sintering to decompose the photopolymer matrix. Few studies have investigated the optical properties of green-state (as printed) ceramic-filled composites. Additionally, there appears to be no research into the potential of non-polar polymer powder-filled photopolymers, which could offer unique optical properties, owing to the high transparency of certain non-polar polymers.

This study will aim to characterize the optical properties of both ceramic-filled and polymer powder-filled photopolymers, without thermally processing samples. To evaluate whether these composites exhibit higher transparency to THz radiation which could be a solution to produce more efficient quasi-optical components through SLA.

II. METHODOLOGY

Polytetrafluoroethylene (PTFE) and silica (SiO_2) were chosen as filler materials owing to their high transparency to THz radiation.

A commercially available silica-filled photopolymer resin, with a silica weight ratio of approximately 66% was chosen. This proprietary material was supplied by Formlabs.

The PTFE-filled photopolymer was formulated in-house. PTFE powder, with an average particle size of 6 – 9 μm, supplied by Sigma Aldrich UK, was gradually added to the photopolymer over 15 minutes, while the mixture was magnetically stirred at 250 rpm. Once mixed, the resin was then stirred for an additional 30 minutes. The weight ratio of PTFE powder in the resin was 28.57 %. Samples were also produced from a commercially available standard photopolymer, Vero White™, supplied by Stratasys to allow for comparisons.

A CAD model of a cylindrical disk with a diameter of 25 mm and a thickness of 1 mm was created using Fusion 360, an Autodesk CAD software. The model was then exported as a .STL file and imported into the appropriate slicing software.

The silica-filled photopolymer sample was printed on a Form 2 SLA printer (Formlabs) using Preform V2.3.3 to generate the G-code. The PTFE-filled and standard photopolymer samples were printed on a Sonic 4K mini masked-stereolithography printer (Phrozen). Chitubox V2.3 was used to prepare the G-code file for the Sonic 4K mini.

Samples were polished using an automatic polisher (LaboPol-20, Struers) with a 600-grit wheel at 100 RPM for 2 minutes, followed by a 1000-grit wheel at 200 RPM for 2 minutes.

A broadband THz time-domain spectroscopy (THz-TDS) system was used to characterize the optical properties of the samples from 0.5 to 2 THz. The THz-TDS system setup has been previously documented in existing literature [6]. Five scans were recorded for each sample, with the sample holder moving in a vertical direction by 1 mm following each scan. To minimize water vapor absorption the system was purged with dry air, maintaining a relative humidity of <1%.

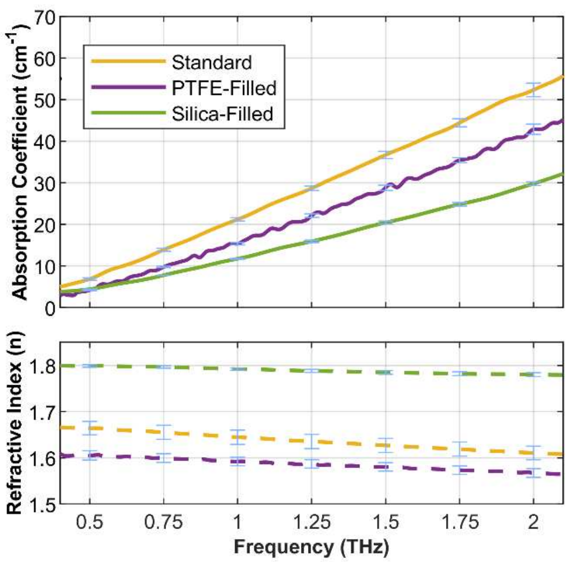

Fig. 1. Mean absorption coefficients (solid lines, upper subplot) and refractive indices (dashed lines, lower subplot) of photopolymer and composite photopolymer samples from 0.5 to 2.0 THz. Error bars represent the standard deviation from five measurements.

III. Results and discussion

Fig. 1 shows the absorption coefficients and refractive indices of the standard and composite photopolymer samples from 0.5 to 2.0 THz. Composite samples exhibited greater transparency to THz radiation compared to the standard photopolymer. At 1 THz the standard photopolymer had an absorption coefficient of 21.2 cm^{-1} ± 0.4, while the PTFE-filled and silica-filled composites had absorption coefficients of 15.3 cm^{-1} ± 0.3 and 11.7 cm^{-1} ± 0.1, respectively. This represented a decrease of 27.65 % for the PTFE composite and 44.60 % for the silica composite.

The silica-filled photopolymer had the highest refractive index at 1 THz (n = 1.790 ± 0.003), followed by the standard photopolymer (n = 1.640 ± 0.016), and finally the PTFE-filled photopolymer (n = 1.590 ± 0.009).

This work demonstrates that incorporating a highly transparent filler material into a photopolymer matrix resulted in composites with significantly reduced absorption coefficients as observed by both the PTFE-filled and silica-filled composites. Additionally, tailoring the refractive index with high-refractive index materials, such as silica, enables greater design flexibility. This work could enable the production of more efficient quasi-optical designs via SLA.

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Author Contributions

L. Phillips: Writing — original draft, Investigation (lead), methodology, visualization; H. J. Godden: Investigation; N. R. Fox: Resources; A. Valavanis: Supervision, Funding acquisition, Writing — review & editing; A. D. Burnett: Supervision, Writing: review & editing, R. Kay — Conceptualization, Supervision, Writing — review & editing; E. Saleh — Conceptualization (lead), Supervision (lead), Writing — review & editing.

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Data Availability Statement

The data associated with this paper is openly available from the University of Leeds data repository. http://doi.org/ (to be confirmed)

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