THz Dielectric Properties of 3D Printable Silica Nanoparticle-based Photoresin

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***Abstract*—GP-Silica, a newly developed photoresin embedded with silica nanoparticles useable with two-photon polymerization, aims to address the lack of low-loss material in the THz range. To determine its suitability for THz device fabrication, its dielectric properties were extracted over the range of 0.5 – 1.5 THz. Its refractive index was found to outperform other 3D printable materials by 1.2 – 1.4 times while its absorption coefficient was almost 5 times lower at 1 THz. The data shared cements the potential of not only GP-Silica but also two-photon polymerization for THz device manufacturing.**

I. INTRODUCTION

BEFORE THz technologies can be applied on a commercial scale, certain issues must first be addressed, some of which are the lack of manufacturing techniques that can match the demanding accuracy requirement of THz devices as well as the absence of a low loss material in the THz range.

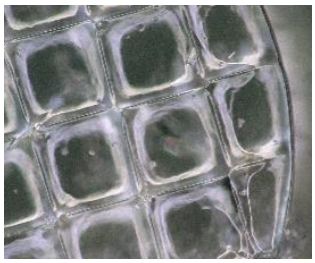


Fig. 1. 3 mm GP-Silica sample fabricated using two-photon polymerization.

As traditional manufacturing techniques cannot be used for complex 3D structures, research has been directed towards additive manufacturing (AM). Attempts have been made to use AM techniques to fabricate sub-THz devices with only a few having been successful due to the demanding surface finish accuracy above 100 GHz [1], [2]. Currently, only one technique may be able to provide a solution given its sub-micron resolution, print volume capability and surface roughness finish: two-photon polymerization (TPP) [3]. Though harboring great potential, current photoresins used with TPP are too lossy in the THz range rendering their use impractical.

The following sections outline the work carried out to characterize the dielectric properties of GP-Silica (Figure 1), a photocurable binder matrix encapsulating silica nanoparticles, that can be used with TPP that addresses the demand for a low-loss material in the THz range.

II. MATERIALS AND METHOD

A. Sample Preparation

The samples tested along with thicknesses are provided in Table 1.

Table 1: Sample Thicknesses

AM Machine	Sample	Thickness (μm)
Photonic Professional GT2	GP-Silica	550 - 570
Photonic Professional GT2	IP-Q	1230
Photonic Professional GT2	IP-S	1140
Photonic Professional GT2	IP-G	390
Stratasys Objet30 Prime	Enduro	2020
Stratasys Objet30 Prime	Veroblue	2010

The 3 mm diameter GP-Silica sample was manufactured in two stages:

1) Firstly, GP-Silica resin was deposited on a silicon substrate and placed in a Photonic Professional GT2 which formed the desired geometry. The geometry was immersed in methanol and isopropanol for 10 min and 1 min, respectively, to remove unpolymerized material. Polymerized binder matrix was removed at 600°C.
2) A sintering stage then followed. Utilizing a DEKEMA Austromat 674S at 1300°C facilitated the melting of silica nanoparticles within the sample causing a reduction in volume and the fusion of individual nanoparticles into a single structure of silica glass.

IP-Q, IP-S and IP-G samples were fabricated by placing liquid resin on a glass substrate and curing under a UV torch until solid. Stereolithography was employed to prepare Enduro and Veroblue samples, in this instance the default settings of the 3D printer were used.

B. THz- TDS System & Data Acquisition

Using a commercial THz-TDS system (Toptica TeraFlash Pro Dual) in transmission modality [4], the dielectric properties (refractive index (n), absorption coefficient ($\alpha = 2\omega\kappa(\omega)/c$, where κ is the extinction coefficient) of the six photoresins listed in Table 1 were determined [5]. The system possessed a beam waist between 0.4 to 0.9 mm at frequencies in the range of 1 – 2.5 THz.

A software (Teralyzer) was used to iteratively solve the transfer function resulting from the normalized frequency-domain spectra of a measured sample [6], [7]. The solution to the transfer function allows for the extraction of dielectric properties of samples.

C. Additional Characterisation

As seen in Fig. 1, the GP-Silica sample was not a single structure but instead consisted of several 300 x 300 μm blocks that were stitched together. To determine if the boundaries between each block yielded scattering that may have influenced the dielectric properties retrieved, the area illuminated by the

THz pulse was varied using different pinhole diameters (200 to 2000 µm). Using this range, the area exposed to the pulse was changed from a single block to almost the entirety of the sample.

III. Results

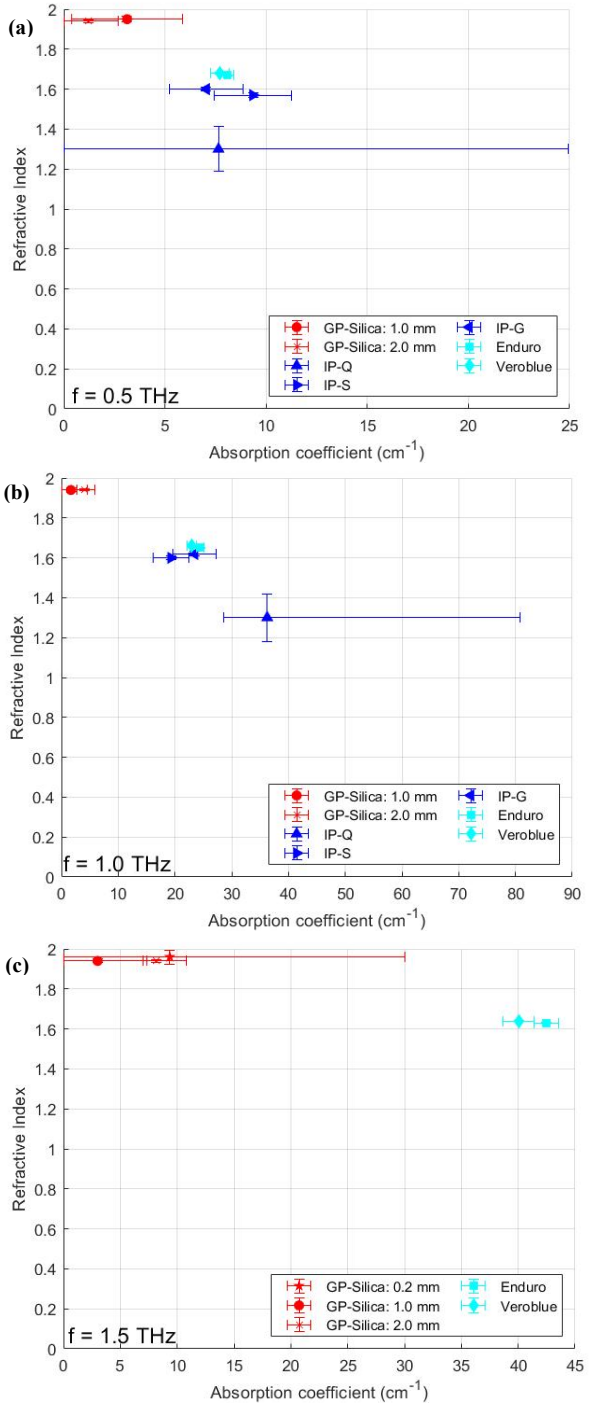


Fig. 2. *n* vs. α for the six photoresins tested at three representative frequencies, with error bars related to standard deviation.

Figures 2(a), (b) and (c) display the *n* vs. α for the photoresins tested at frequencies of 0. 5, 1.0 and 1.5 THz, respectively. The general trend in each graph remains consistent with GP-Silica consistently being situated on the upper left area of the graph due to its higher refractive index and lower absorption coefficient, regardless of the pinhole diameter used. This not only shows that GP-Silica is able to outperform the other 3D printable materials but also confirms that the boundaries between GP-Silica blocks have a negligible influence on the extracted dielectric properties of the sample. This conclusion is further cemented by the overlap of error bars for the GP-Silica data.

Across all frequencies, GP-Silica exhibits an *n* between 1.94 to 1.96. In contrast, the next best performing material, Veroblue, presents a refractive index 1.2 times lower at values of 1.66 – 1.68. A high refractive index is preferable for device miniaturization. The difference is even more significant when comparing the absorption coefficients of samples. At 1 THz, GP-Silica exhibited an absorption coefficient between 1.6 cm^{-1} and 4.0 cm^{-1}. The absorption coefficients of IP-Q, IP-S, IP-G, Enduro and Veroblue at the same frequency are 19.31 cm^{-1}, 23.46 cm^{-1}, 36.25 cm^{-1}, 24.42 cm^{-1} and 22.93 cm^{-1}, respectively. In this case, the next best performing material, IP-Q presents an α almost 5 times larger than GP-Silica. At the highest frequency presented, 1.5 THz, the α of GP-Silica still remains fairly low, between 8.12 to 9.36 cm^{-1}. Those of Enduro and Veroblue lie above 40 cm^{-1}, while the absorbance of IP-G, IP-Q and IP-S is so strong at 1.5 THz that the sample signal could no longer be differentiated from the noise floor and so no reliable data could be extracted.

IV. Summary

The dielectric properties of GP-Silica in the frequency range of 0.5 – 1.5 THz were acquired using a THz-TDS system. Even using the highest estimates for the dielectric properties of GP-Silica, the values it presented for *n* (or equivalently ε_r) were still 1.2 – 1.4 times better than the next closest material, while for *α* (or equivalently tanδ) at 1 THz, it showcased values almost 5 times smaller than the other samples. Through the data provided the potential of GP-Silica to address the demand for low-loss materials as well as the possibility of two-photon polymerization for high resolution fabrication of THz devices was established.

References

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