Modified elastomeric polymers for loss reduction in the terahertz range

Daniel Headland,* Peter Thurgood,† Daniel Stavrevski,† Withawat Withayachumnankul,*†‡ Derek Abbott,*
Madhu Bhaskaran,† and Sharath Sriram†
*School of Electrical & Electronic Engineering, The University of Adelaide, SA 5005, Australia
†Functional Materials and Microsystems Research Group, RMIT University, Melbourne, VIC 3001, Australia
‡ Interdisciplinary Graduate School of Science and Engineering, Tokyo Institude of Technology,
Ookayama, Meguro-ku, Tokyo 152-8552, Japan

***Abstract*—A method of reducing the dielectric loss of polydimethylsiloxane (PDMS) in the terahertz range with dopants is presented. Samples of PDMS are doped with varied concentrations of polytetrafluoroethylene (PTFE) micro-particles, and characterized with terahertz time domain spectroscopy (THz-TDS) in order to extract their material properties. It is found that controlled doping can significantly reduce dielectric loss in PDMS at terahertz frequencies, and for the sample with highest dopant concentration, a 15.3% average reduction in loss tangent is demonstrated over a range from 0.3 to 1 THz. Measured material properties are compared with the Lichtenecker logarithmic mixture formula, and approximate agreement is attained.**

I. Introduction

ELASTOMERIC polymers are often utilized as dielectrics in the terahertz range, owing to their compatibility with microfabrication techniques, which makes it possible to fabricate layers of micron-scale thickness. Polymers such as PDMS are therefore used extensively in terahertz metamaterial [1] and reflectarray applications [2]. However, these polymers have significant loss, which is exacerbated by field confinement in resonant devices, and this can impact performance. This work presents a method of reducing the dielectric loss of the polymer polydimethylsiloxane (PDMS) by doping with polytetrafluoroethylene (PTFE) micro-particles [3]. Given that the particles are sub-wavelengh, and roughly evenly distributed through the polymer, the resultant materials form effective media. Similar techniques have previously been demonstrated in the terahertz range to improve the performance of Dällenbach absorbers [4], and to increase the refractive index of a dielectric [5].

II. Fabrication and results

A known amount of liquid PDMS (a 1:10 mixture of curing agent and pre-polymer) is mixed with a known amount of dopant to yield a desired mass percentage, and then poured onto a smooth silicon wafer. The average size of dopant micro-particles is than 12 µm, which is clearly sub-wavelength in the relevant frequency range, as the wavelength at 1 THz is equal to 300 µm. Sample mixtures were then placed in a vacuum chamber for a period of two hours, and finally the samples were cured at room temperature and atmospheric pressure over a period of 48 hours. Scanning electron microscope (SEM) images of the fabricated PTFE samples are given in Fig. 1.

Samples doped to 10%, 20%, and 40% PTFE by mass were prepared and characterized using terahertz time domain spectroscopy (THz-TDS), using air as a reference. In order to account for variation in sample thickness and dopant aggregation, measurements were taken at five arbitrary locations on the surface of each sample. Material properties were extracted using a standard parameter estimation process [6], and the calculated loss tangent of all samples is given in Fig. 2. It can be seen that doped samples exhibit reduced loss tangent, with the sample of highest dopant concentration having the lowest loss. The average loss tangent of the pure PDMS sample is 0.058 over a frequency range from 0.3 THz to 1.0 THz, and

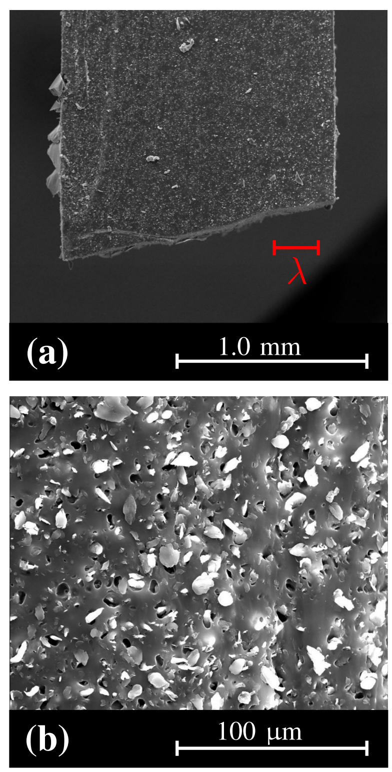

Fig. 1. Scanning electron microscope (SEM) images of polymer sample that is doped to 40% PTFE by mass at (a) 100×, and (b) 1000× magnification. Scale of wavelength at 1 THz is shown in red.

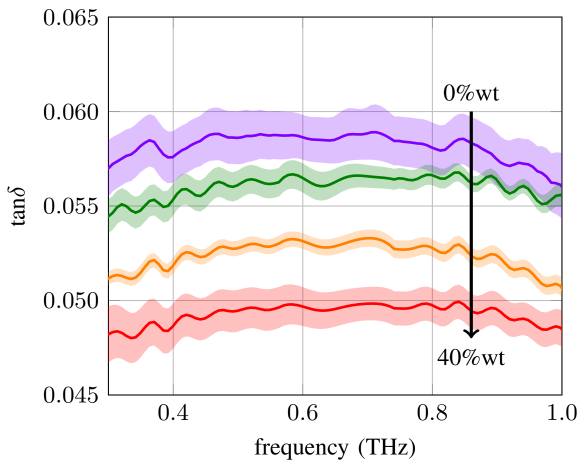

Fig. 2. Loss tangent of PTFE-doped PDMS samples. Error bars are shown with colored regions.

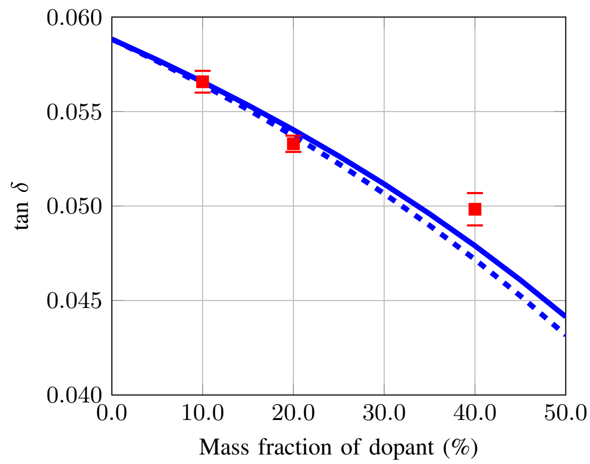

Fig. 3. Comparison with effective medium theory at 0.7 THz. Measured values are shown with markers, with error bars. The dashed curve considers only the two lowest dopant concentrations.

the average loss tangent of the sample that is 40% PTFE by mass is 0.049 over the same range, hence the addition of the powder dopant has reduced the loss tangent of the polymer by 15.3%.

In order to further investigate the material properties of the doped polymer samples, effective medium theory is employed. This investigation is performed at 0.7 THz, as this is the frequency at which the relevant THz-TDS system dynamic range is at maximum. The Lichtenecker logarithmic mixture formula is selected as it is valid for randomly oriented, randomly shaped inclusions [7], which, from Fig. 1, is representative of the samples in question. This formula is given in Equation 1, where ϵ is complex permittivity and $f_{v,n}$ is the volume fraction of the nth material in the mixture.

$$\epsilon_{\text{eff}} = \prod_{n=1}^{N} \epsilon_n^{f_{v,n}} \tag{1}$$

In this case, $N = 2$, as each sample is a two-part mixture. In order to apply this formula, the material properties of the bulk dopant are estimated from the measured results by substituting extracted material properties of doped samples for ϵ_{eff}, substituting the material properties of undoped PDMS for ϵ_1, and re-arranging to extract ϵ_2. This procedure was performed for all doped samples, and the mean of extracted complex relative permittivity values is $\hat{\epsilon_2} = 2.711 + j0.032$. Finally, this mean value of bulk dopant permittivity was used to predict the material properties of samples with dopant concentration ranging from 0% to 50%. The loss tangent determined from this procedure is given in Fig. 3, and is in approximate agreement with experiment. As the greatest deviation from theory is for the sample of highest dopant concentration, we ascribe this deviation to agglomeration of dopant particles, which compromises homogeneity and increases loss.

In order to mitigate the impact of agglomeration on the effective medium theory procedure, the complex relative permittivity of the dopant is recalculated using only the results from the 10% and 20% doped samples as $\hat{\epsilon_2} = 2.959 + j0.026$. The predicted loss tangent using this updated value of permittivity is given in Fig. 3. It can be seen that the predicted loss tangent has increased agreement with the relevant experimental data points, and is now within the error bars.

III. Conclusion

It is possible to reduce the loss tangent of elastomeric polymers with dopants. PDMS samples doped with 40% PTFE by mass exhibit a 15.3% reduction in loss tangent. Material properties are compared to effective medium theory, and approximate agreement is attained, with deviation due to agglomeration of dopant particles.

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