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Resonant Terahertz Absorption in Carbon Microfibres

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Abstract – **Microsized carbon fibres exhibit strong resonant absorption at terahertz frequencies. Using near-field terahertz time-domain spectroscopy, we probe their conductivity by analysing the degree of field enhancement produced by plasmonic resonances. We demonstrate, theoretically and experimentally, the potential usability of carbon microfibres as terahertz absorbers with engineerable response.**

I. Introduction

Terahertz (THz) conductive properties of semiconductors and semimetals are similar those of metals at optical frequencies. THz plasmonics develops methods bringing plasmonic effects, such as field-enhancement, field localisation, and resonant absorption, to frequencies between microwaves and the visible spectrum.

Probing the conductivity of individual, weakly-conductive particles is essential for developing THz plasmonic macro-devices including tunable plasmonic metamaterials. The most common experimental technique used for this purpose is the indirect conductivity probing via THz spectroscopy of composites containing multiple samples [1]. Effective media approximations are then used to extract the properties of individual particles. However, such methods are not applicable to composites with inhomogeneous, resonant or irregularily shaped inclusions [2].

We performed near-field time-domain THz spectroscopy [3] on individual resonant weakly-conductive particles - carbon microfibres (CMFs) - to probe their real THz conductivity. The latter strongly influences the resonance frequencies of these lossy dipoles, as well as the degree of near-field enhancement induced around them by the incident THz pulse. Comparing our measured data to the predictions obtained via full-wave numerical modelling, we were able to estimate the real conductivity of each of the samples. Having confirmed that the THz conductivity of CMFs corresponds to the condition maximizing the dipole absorption to scattering ratio, we propose their use as THz absorbers with engineerable absorption profile.

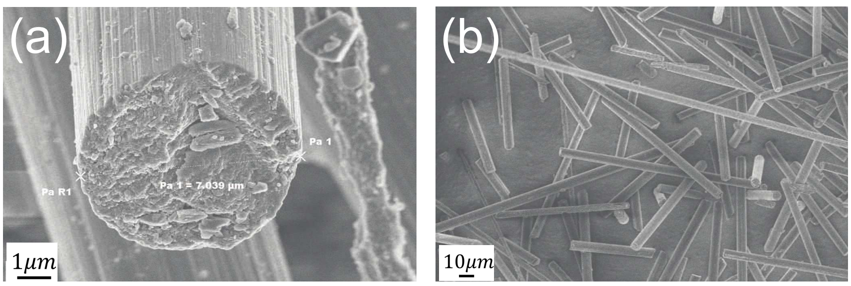

Fig. 1: SEM images of milled CMFs.

II. CMFs as lossy THz dipoles

CMFs are microsized plasma-chemically treated and milled carbon fibres. Their SEM images are shown in Fig. 1. The CMFs are $\approx 7\ \mu$m in diameter, and their lengths vary from $10\ \mu$m to $150\ \mu$m. With their sizes comparable to $\lambda/2$, the CMFs support plasmonic dipole resonances at THz frequencies.

With 98% carbon basis, and given the fact that graphite's plasmon frequency is ≈ 34 THz, it is to expect that the conductivity of CMFs is high enough for them to exhibit metallic response in the THz frequency band.

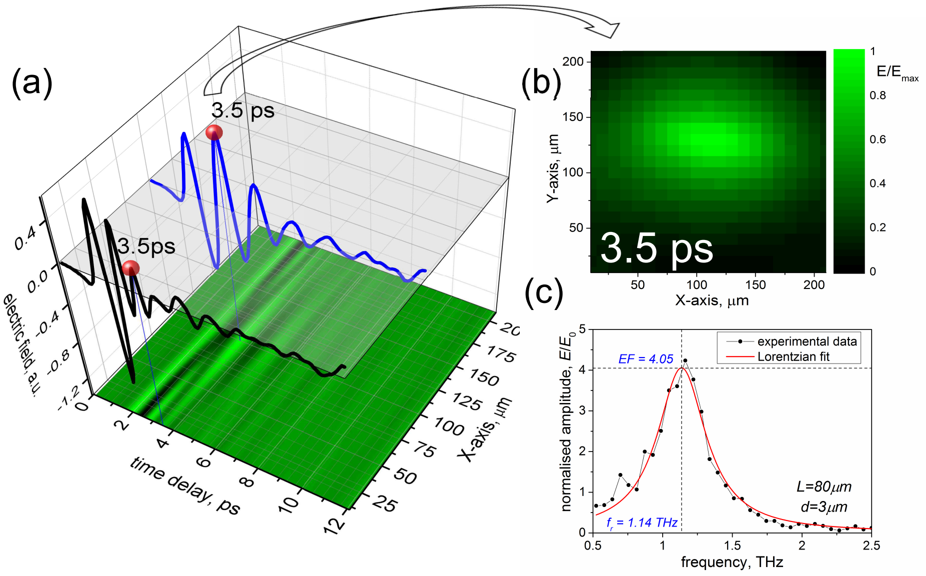

Fig. 2: (a) The curves are time-domain signals detected in front of (blue) and away from (black) the $80\ \mu$m CMF placed at a distance $d = 15\ \mu$m away from the probe. The bottom of the plot is the space-time diagram showing how the detected waveform changes as the probe scans along the sample. (b) THz near-field image of the CMF taken at a fixed time delay of 35 ps. (c) Normalised spectrum and its Lorentzian fit of the same CMF placed at $d = 3\ \mu$m away from the detector.

III. Near-field THz conductivity probing

We performed aperture-based near-field THz time-domain spectroscopy on individual CMFs and confirmed their resonant THz response (Fig. 2). Each sample was glued to a low density polyethylene (LDPE) film and placed in front of a $10\ \mu$m aperture probe. The CMFs were exposed to broadband THz pulse covering the frequency range of $0.5 - 2.5$ THz.

The THz conductivity of the samples was extracted from the enhancement of the near-field induced around them by the incident THz pulse, as well as the shift between their resonance frequencies and that of the corresponding perfectly conducting dipole. The CMF conductivity was experimentally estimated as $\approx 1 - 5 \cdot 10^4$ S/m. This value is very close to the condition maximizing the absorption to scattering ratio of resonant dipoles [4].

IV. Engineerable THz absorption in CMF composites

We studied composites consisting of high density polyethylene (HDPE) base with arbitrarily oriented and differently sized CMF inclusions. Using time-domain spectrometer Teraview TPS Spectra 3000, we measured the absorption coefficients of thin pellets ($1 - 2$mm) of such composites (Fig. 3a). All curves are plotted within the dynamic range of the spectrometer, determined as in [5] (dashed curves are to guide the eye). CMF composites demonstrate a clearly resonant behaviour: broad absorption peaks at around 1.5 THz indicate the presence of

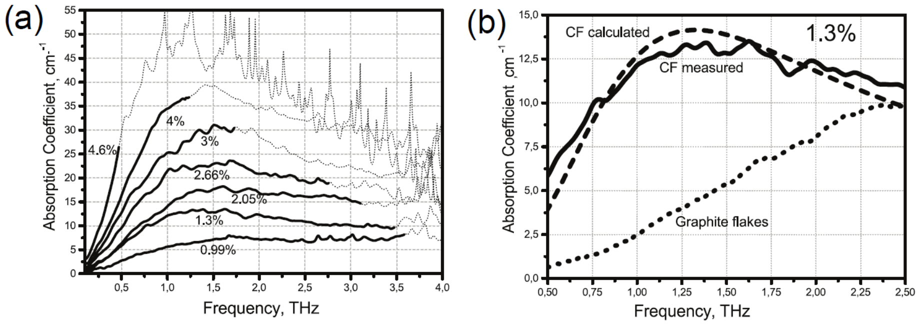

Fig. 3: (*a*) Experimentally obtained absorption coefficient of CMF/HDPE composites at different CMF concentrations (weight fractions shown in the plot). (*b*) Theoretically predicted and measured absorption coefficients of a 1.3% CMF/HDPE composite. Measured absorption coefficient of a 1.3% graphite flakes/HDPE composite is shown for comparison.

size effects distributed over lengths of CMFs in each sample. The absorption coefficient depends linearly on the concentration of CMF, and grows more rapidly in the vicinity of the resonance frequency.

Very high level of absorption at THz frequencies and a pronounced resonance behavior makes the spectroscopy of composites with higher concentration of CMFs extremely difficult. To obtain these spectra numerically, we combined the effective medium approximation and a simple dipole antenna model [6]. We used the method-of-moments to model the scattering and absorption properties of CMFs considering them as lossy dipoles. This simple semi-analytical approach confirmed the spectral positions of measured resonances and allowed to predict absorption spectra of CMF composites with different lengths distributions (Fig. 3*b*).

V. Conclusion

We present an experimental technique for non-contact probing of THz conductivity of resonant, weakly conductive dipoles using near-field THz spectroscopy. We measured THz conductivity of CMFs and showed that it corresponds to efficiently absorbing resonant dipoles. Having the freedom of artificially creating any distribution of CMF lengths, we may pre-design the absorption profiles of the composites. In particular, almost flat absorption spectra are achievable in the THz frequency range. The simplicity of the model as well as low fabrication costs make CMFs worth further consideration for THz plasmonics and metamaterials applications.

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References

[1] J. Lloyd-Hughes, T.-In Jeon,, "A Review of the Terahertz Conductivity of Bulk and Nano-Materials," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 33, no. 9, pp. 871-925, 2012.
[2] A.H. Sihvola, *Electromagnetic Mixing Formulas and Applications*, London: Institution of Electrical Engineers, 1999.
[3] O. Mitrofanov, "Collection-mode near-field imaging with 0.5-THz pulses," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 7, no. 4 pp. 600-607, 2001.
[4] S. Tretyakov, "Maximizing Absorption and Scattering by Dipole Particles," *Plasmonics*, vol.9, pp. 935-944, 2014.
[5] P.U. Jepsen, B.M. Fischer, "Dynamic range in terahertz time-domain transmission and reflection spectroscopy," *Optics Letters*, vol. 30, pp. 29-31, 2005.
[6] R.E. Colin, *Antennas and Radiowave Propagation*, New York: McGraw-Hill Book Company, 1985.