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A flexible ultra-wideband terahertz absorber based on vertically aligned carbon nanotubes

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Abstract

Ultra-wideband absorbers have found wide applications in wireless communications, energy harvesting and stealth applications. Herein, with the combination of experimental and theoretical analyses, we develop a flexible ultra-wideband terahertz (THz) absorber based on vertically aligned carbon nanotubes (VACNTs). Measured results show that the proposed absorber is able to work efficiently to cover the entire THz region (e.g., 0.1 to 3.0 THz), with an average power absorptance of >98%. The total thickness of the device is about 360 μm , which is only 1/8 of the wavelength for the lowest evaluated frequency of 0.1 THz. More importantly, our device can function normally, even after being bent up to 90° or after 300 times of bending. The new

insight into the VACNT materials paves the way for applications such as radar cross-section reduction, electromagnetic interference shielding and flexible sensing.

Keywords

terahertz, carbon nanotubes, absorption, flexible, ultra-wideband

Introduction

Materials with broadband and high absorption characteristics are essential in many applications such as radar cross-section (RCS) reduction, wireless communications, imaging, thermal emission and energy harvesting. In the terahertz (THz) range, bulk materials can exhibit good absorption performance in certain frequency bands. However, traditional materials are not be able to provide near unity power absorptance over the entire 0.1 to 3.0 THz band. Therefore, it is still in great demand for highly absorbing materials with ultra-wideband and flat power absorptance in the THz range.

Metamaterials, which are artificial composites whose electrical/optical properties can be engineered by their structures rather than the materials they are composed of, have shown great potential to realize perfect absorbers across the microwave to optical frequency regions.¹ Metamaterial-based absorbers normally consist of an array of resonators backed with a dielectric spacer and a metallic ground plane.² When the impedance of the device Z is matched to the impedance of free-space Z_0 , perfect absorption A can be achieved according to $A = 1 - R = 1 - \left| \frac{Z-Z_0}{Z+Z_0} \right|^2$, as the transmittance T is zero due to the presence of the ground plane. Unfortunately, metamaterial-based perfect absorbers (MPAs) have inherently narrow bandwidth because of the resonating nature of unit cells. Although it is easy to obtain single- or multi-band MPAs,³⁻⁸ achieving broad bandwidth remains a challenge.⁹

Various techniques have been implemented to expand the bandwidth of MPAs. One of the most common approaches for broadband absorption is to use vertically stacked multi-layer structures or horizontally arranged multiple resonators, so that the absorption peaks of different layers/resonators will be overlapped to create a broadband overall absorption.^{10–14} Another approach utilizes intrinsic high loss dielectrics or semiconductors to achieve wideband absorption using relatively simpler structures.^{15–19} However, the former approach faces an increased design and fabrication complexity, while the latter still shows dependence on the properties of lossy dielectrics it uses. In addition to MPAs, one possible strategy for achieving ultra-wide band absorption performance is to use low reflective surface structures with a high lossy skeleton material. For example, 3D porous MXene/GO foam (MGOF)²⁰ and monolithic three-dimensional cross-linked Fe_3O_4 /graphene material (3DFG)²¹ have been introduced recently with excellent absorption performances in the THz range, showing the potential of 3D porous conductive networks for stealth applications.

In this paper, we demonstrate a flexible ultra-wideband THz perfect absorber based upon vertically aligned carbon nanotubes (VACNTs) on a PDMS substrate and a metallic ground layer. With careful consideration of the VACNT thickness, filling ratio and alignment factor, the reflection can be minimized, while the transmission is completely blocked by the bottom copper layer, yielding a high power absorptance. Numerical results shows that the absorption performance of the device exhibits no resonant behaviour, enabling it to work efficiently within the entire 0.1 to 3.0 THz region. This device can also be used as a perfect absorber within the infrared and visible regions. Considering its simplicity, flexibility, lightweight and cost effectiveness, the proposed absorber is potential to be used for imaging, energy harvesting and RCS reduction applications.

Results and discussion

The schematic and fabrication process of the proposed THz absorber is illustrated in Fig. 1. The VACNT growth was synthesized through a thermal chemical vapor deposition (TCVD) system with Al_2O_3 and Fe as the buffer layer and catalyst, respectively. A copper (Cu) layer was deposited onto a PET substrate, and spin-coated by a PDMS layer, constructing the target substrate. A transfer process was used to transfer the VACNTs from the Si substrate to the PDMS/Cu/PET substrate. The operating principle of our absorber is similar to most MPAs, where the PDMS spacer is used as substrate of VACNTs, and the Cu layer on top of the PET substrate is applied to block the transmission. Therefore, by minimizing the power reflectance R , a high power absorptance A can be achieved. However, in order to achieve an ultra-wideband and excellent absorption performance, no metallic or dielectric resonators are used. Instead, VACNTs are introduced as the only absorbing material for this device.

Figure 1: Schematic of fabrication process for the proposed flexible THz absorber.

Fig. 2(a) demonstrates the fabricated THz absorber. The overall size of the sample is $2.5 \times 2.5 \text{ cm}^2$, with an effective VACNT area of $1.5 \times 1.5 \text{ cm}^2$. In order to apply VACNTs for efficient THz wave absorptions, VACNT thickness is the most crucial parameter. Experiments suggest that the thickness of CVD-grown VACNTs shows a strong dependence

on the growth time, which is about 1 mm/hour. In our lab, VACNTs as thick as 4 mm can be fabricated. A thicker array will introduce a longer propagation path for the incoming THz waves, and as a result, increase the power absorptance. A compromise, however, has to be made between the power absorptance and the overall device thickness. We fabricated samples with two different VACNT thicknesses, which are 300 μm and 450 μm , respectively. As will be seen later, these two values are thick enough to provide near-unity absorption performances.

Figure 2: Photograph and SEM images of the VACNT-based absorber. (a) Optical image showing the size and flexibility of the THz absorber. Side view of VACNTs of two samples on (b) silicon substrate, and (c) PDMS/Cu/PET substrate. (d) and (e) Side view of VACNTs at different magnifications. (f) Top view of VACNTs. (g) Raman spectra of the absorber. (h) Diameter distribution of VACNTs.

Fig. 2(b) and 2(c) further shows the SEM images of VACNTs on the silicon substrate and the PDMS/Cu/PET substrate, respectively. It is seen that the VACNTs have been successfully transferred and a good alignment can be observed after the transfer process. Fig. 2(d) to (f) further illustrate the side and top views of the VACNTs. Raman spectra of VACNTs in Fig. 2(g) clearly show the *D* and *G* bands of graphite at approximately 1350 and 1570 cm^{-1} on both the silicon and PDMS substrate, indicating there was no significant

degradation in the quality of the VACNTs before and after the transfer. Furthermore, a slightly lower I_D/I_G ratio was observed after the transfer process. This is due to the existence of amorphous carbon on top of VACNTs on silicon substrate, which has a broad carbon Raman band peaking between 1500 and 1600 cm^{-1} .²² After the transfer process, the VACNT was upside down with less amorphous carbon on top, resulting in a lower I_D/I_G ratio. Another possible reason is that the VACNT array was treated at a temperature of 500 °C under a weak oxidation environment for 5 mins. This may also reduce the content of amorphous carbon, as evidence in.²³

Apart from VACNT thickness, other parameters such as the filling ratio and the alignment factor, have to be carefully considered as well. The filling ratio f is defined as the volume fraction of graphite rods. Given the same VACNT thickness and alignment factor, a low filling ratio will effectively reduce the reflectance at the air-VACNT interface, but the absorption will also be reduced due to a smaller CNT frontal area. Fig. 2(h) illustrate that the diameter of VACNTs ranges from 10 to 40 μm , with more than 65% locating within 15 to 25 μm . We further measure the spacing distribution of VACNTs, giving values between 30 and 80 μm and maximized at 55 μm . For later material modelling and simulation, we use an average filling ratio of 0.1 calculated from $f = \frac{\pi d^2}{4a^2}$, where $d = 20 \mu\text{m}$ and $a = 55 \mu\text{m}$, representing the average diameter and spacing of VACNTs, respectively. Our calculation agrees well with typical filling ratio for typical CVD-grown VACNTs, which is between 0.01 and 0.15²⁴. Furthermore, the alignment factor χ can be calculated using $\chi = \cos \theta$, where θ is the tilt angle between the VACNTs and the vertical direction²⁵. It has been found that perfectly aligned VACNTs (e.g., $\chi = 1$) are not ideal for electromagnetic wave absorptions, even it demonstrates the lowest reflectance at the air-VACNT interface.²⁵ For our fabricated samples, the tilt angle $\theta \approx 18^\circ$ according to SEM measurements, giving $\chi \approx 0.95$. Therefore, $\chi = 0.95$ is chosen for the modelling of VACNTs.

Using the refractive index data of graphite²⁶ and Maxwell-Garnett theory,²⁷ the real (n_{VACNT}) and imaginary (k_{VACNT}) part of the effective complex refractive index $\tilde{n}_{VACNT}$

for the VACNT array can be calculated, as shown in Fig. 3. It can be seen that at the infrared regime, n_{VACNT} is approaching to unity, resulting in an ultra-low reflectance from VACNTs. Within the THz range (e.g., at 0.3 THz), however, the refractive index increases to ~ 1.4 , and $R = \left| \frac{n_{air} - \tilde{n}_{VACNT}^2}{n_{air} + \tilde{n}_{VACNT}^2} \right|^2 = 0.05$. This validates that most of the power of the incident THz waves will be able to transmit through the air-VACNT interface. As long as the transmitted THz waves can be absorbed by the VACNTs, a high power absorptance can be obtained since the transmittance is zero for the proposed absorber. Further reducing the filling ratio will provide a lower $\tilde{n}_{VACNT}$, and thus a lower R at the air-VACNT interface. However, this will require thicker VACNTs in order to obtain the same level of absorption performance.

Figure 3: Calculated real and imaginary part of the effective complex refractive index of the VACNT array for $f = 0.1$ and $\chi = 0.95$.

The calculated effective complex refractive index of VACNTs are then input into the commercial electromagnetic simulator CST MICROWAVE STUDIO® to model the material in the software. The dielectric properties of PDMS are set to $\epsilon_r = 2.5$ and loss tangent $\tan \delta = 0.05^{28}$ for full-wave simulations.

Due to the simplicity of the proposed structure, only two parameters, which are VACNT thickness t_{VACNT} and PDMS thickness t_{PDMS} , need to be considered. The average power absorptance (A_{avg}) between 0.1 and 3.0 THz was simulated to investigate the dependence

of the absorption performance on t_{VACNT} and t_{PDMS} . From Fig. 4, it can be seen that the A_{avg} mainly depends on the thickness of VACNT. For $t_{VACNT} \leq 150 \mu\text{m}$, maximum average power absorptance is less than 0.90. Once $t_{VACNT} > 240 \mu\text{m}$, A_{avg} is greater than 0.95 between 0.1 and 3.0 THz, for all considered t_{PDMS} values between 10 and 100 μm . It further increases to 0.97 and 0.98 for $t_{VACNT} \approx 300$ and 400 μm , respectively. Not much improvement on the average power absorptance was observed by further increasing t_{VACNT} . For later experimental demonstrations, $t_{VACNT} = 300 \mu\text{m}$ and $t_{VACNT} = 450 \mu\text{m}$ are chosen to fabricate the proposed THz absorber, and $t_{PDMS} = 65 \mu\text{m}$ for these two t_{VACNT} values.

Figure 4: Simulated average power absorptance of the proposed absorber between 0.1 and 3.0 THz as a function of (a) t_{VACNT} and t_{PDMS} , and (b) t_{VACNT} for $t_{PDMS} = 65 \mu\text{m}$.

The fabricated flexible THz absorbers with different VACNT thicknesses were measured using a terahertz time-domain spectrometer (THz-TDS) Zomega-Z3. Reflection-mode setup was used to measure the amplitudes and phases of reflected signals, and then normalize to a silver mirror to obtain the power reflectance R . The power absorptance A can be simply calculated by $A = 1 - R$. At normal incidence, the power absorptance from 0.1 to 3.0 THz of the two samples are shown in Fig. 5. Overall, measured results show good agreement with simulations, and even better absorption performances were obtained for both samples. This is mainly due to the discrepancy of the material properties of VACNTs between the modelling and the fabrication sample. In simulations,

effective complex refractive index calculated from data of graphite was used, and $f = 0.1$ and $\chi = 0.95$ are fixed average values. While in fact, due to the non-uniformity of the VACNT sample, these values may be slightly different. The tolerances in fabrication also contribute to this discrepancy. Furthermore, at low frequencies, ripple-like responses were observed for both simulated and measured results. This is due to multiple reflections between the air-VACNT and VACNT-PDMS interfaces. For example, the sample with $t_{VACNT} = 300 \mu\text{m}$ is approximately $1/4 \lambda_c$, where $\lambda_c = 1171 \mu\text{m}$ is the wavelength in VACNTs, causing a reflection minimal and thus an absorption peak at about 0.16 THz. In general, two samples both demonstrate near-unity absorption performances, having a measured average power absorptance of 0.989 and 0.993, respectively. This confirms that the proposed THz absorber can work effectively within the entire THz (e.g., 0.1 to 3 THz) region. It is also straightforward that the absorber is not sensitive to the polarization of incident waves, considering the structure of VACNTs.

Figure 5: Measured power absorptances between 0.1 and 3.0 THz for the fabricated THz absorbers. (a) $t_{VACNT} = 300 \mu\text{m}$. (b) $t_{VACNT} = 450 \mu\text{m}$.

We further investigate the angle dependence of the THz absorbers by employing a theta-to-theta module in the reflection-mode setup, with which the incident and reflected angles can be adjusted from 15° to 60° simultaneously. By measuring the power reflectance, we can obtain the power absorptance between 0.2 and 2.4 THz as a function

of the incident angle, as shown in Fig. 6. It should be noted that when compared with experimental setup for normal incidence, the signal-to-noise ratio is lower at oblique incidence due to a longer optical path and loss from additional beam splitters. Therefore, results within 0.1-0.2 THz and 2.4-3.0 THz were not illustrated in the figures. As expected, the sample with $t_{VACNT} = 450 \text{ } \mu\text{m}$ shows better absorption performances than those of $t_{VACNT} = 300 \text{ } \mu\text{m}$ sample for all incident angles. As the incident angle increases, the average power absorptances for both samples decrease, from 0.984 and 0.998 at 15° , to 0.972 and 0.984 at 60° , respectively. The interference features in the absorption spectra at high frequencies are Etalon effect that caused by the echoes from the main peak. Nevertheless, this experiment shows that our absorbers are not sensitive to the incident angle, and can sustain excellent absorption performances with $A_{avg} > 0.97$.

Figure 6: Measured power absorptance for the fabricated THz absorber between 0.2 and 2.4 THz as a function of incident angle from 15° to 60° . (a) $t_{VACNT} = 300 \text{ } \mu\text{m}$ sample. (b) $t_{VACNT} = 450 \text{ } \mu\text{m}$ sample.

To demonstrate the flexibility of the devices, two more experiments were carried out. In the first experiment, the flexible absorber was conformally wrapped around curved objects to investigate the effect of the object shape on the absorption performance. As shown in Fig. 7a, we 3D-printed three sample holders with different sizes to provide a bending angle of 30° , 60° and 90° for the absorbers, respectively. The same reflection-mode experimental setup was used to measure the power absorptance at normal incidence. It is seen from in Fig. 7b and 7c that almost identical power absorptances were obtained for all these bending angles. Slightly differences for different bending angles are due to the change of effective filling ratio after bending. This confirms that this flexible absorber can be applied to curved metallic objects to suppress the reflection, which is a desired feature in camouflage or RCS reduction applications.

Figure 7: Experimental results for bending test 1. (a) Schematic and photograph demonstrating the flexible THz absorber wrapped around curved objects with different bending angles. Measured power absorptance between 0.1 and 2.5 THz for THz absorbers with different bending angles for (b) $t_{VACNT} = 300 \mu\text{m}$ sample and (c) $t_{VACNT} = 450 \mu\text{m}$ sample.

The second experiment aims to find out how the performance of the device changes after different times of bending. In this experiment, we also use the reflection-mode setup for normal incidence. As shown in Fig. 8a and 8b, it is confirmed that the absorption performances were not significantly degraded after bending, with the average power absorptance decreased from 0.989 to 0.984 and from 0.993 to 0.981 for the samples, respectively. A decrease in power absorptance at frequencies below 0.5 THz can be clearly observed. This is possibly due to the defects of VACNTs as well as the change of VACNT thickness, filling ratio and alignment factor, which will in turn change the effective material properties and thus the power absorption. After 300 times of bending, the average power absorptance of the $t_{VACNT} = 450 \text{ }\mu\text{m}$ sample becomes lower than that of the $t_{VACNT} = 300 \text{ }\mu\text{m}$ one. This may suggest that thicker VACNTs are more likely to be damaged during the bending test.

We finally compare the absorption performance of the proposed absorber with other THz absorbers previously demonstrated in literature. It can be seen that metallic metamaterial-based perfect absorbers (MPAs) have near-unity power absorptance and ultra-thin structure. Unfortunately, MPAs suffer from relatively narrow bandwidth due to the resonating nature of the device. Even with multiple resonators or multiple layers, the bandwidths of MPAs are still limited. Patterned graphene or tantalum nitride have also been employed to create broadband MPAs with additional tunability. Doped silicon MPAs have wider bandwidth by combining multiple plasmonic resonances and intrinsic absorption capability of silicon, but the thickness has to be increased to obtain a reasonable power absorptance. By employing a highly lossy porous material with a low reflective surface, a remarkable ultra-wideband absorption from 3.4 GHz to 2.5 THz has been achieved with only a few millimeter sample thickness.²¹

Compared with these results, our proposed absorber shows a power absorptance of >0.9 from 0.1 THz, and remains its excellent absorption performance throughout the entire THz spectrum. More importantly, it can also operate within the infrared and visible

ranges, as VACNTs have been proved as perfect absorbers within these regimes.^{26,29} This will benefit many potential applications such as energy harvesting, imaging and RCS reduction, for which ultra-wideband absorption capability is essential to improve the system performance. It is worth mentioning that 0.1 THz is not the lower frequency limit of the proposed absorber, but is only due to the limited spectral coverage of the THz-TDS used in the experiments. Moreover, by increasing the VACNT thickness or integrating VACNTs with other lossy materials with complementary electromagnetic responses, the absorption performance at lower frequencies (e.g., in the millimeter or sub-millimeter wave range) is expected to be further improved.

Table 1: Comparison of absorption performance of our proposed absorber with representative materials in literature.

Materials	Operating Frequency (THz) (Absorptance > 90%)	FWHM (THz)	Average Absorptance	thickness (mm)	Ref
Metallic MPA (multi-layer)	4.3-5.7	4.1-5.9	~0.97	0.004	30
Metallic MPA (multi-layer)	0.80-1.34	0.76-1.48	> 0.95	0.03	31
Metallic MPA (multi-resonator)	0.22-0.33	0.2-0.36	> 0.93	0.09	32
Patterned graphene MPA	0.95-2.52	0.7-3.0	~0.95	0.03	33
Patterned graphene MPA (multi-layer)	0.55-3.12	0.4-3.4	> 0.93	0.05	34
Patterned graphene + metallic MPA (multi-layer)	1.2-7.5	0.5-10	> 0.95	0.02	35
Doped silicon MPA	0.67-1.78	0.4-	~0.95	0.2	36
Doped silicon MPA	0.98-5.0	0.52-	~0.97	0.09	37
Doped silicon MPA	0.6-10	0.3-	~0.95	0.4	18
Tantalum nitride MPA	1.17-2.99	0.9-3.6	>0.90	0.025	38
3D Fe ₃ O ₄ /graphene	3.4 GHz-2.5 THz	N/A	>0.90	3	21
3D MXene/GO foam	0.2-2	N/A	>0.90	2	20
PMMA/graphite	1.32-1.5	0.25-1.5	>0.90	0.25	39
3D-printed wax	7-40 and 75-110 GHz	N/A	>0.97	6-11	40
VACNT	0.1 THz - visible	N/A	>0.98 >0.99	0.36 0.51	This work

Experimental Section

Fabrication of Flexible THz Absorbers

The VACNTs were synthesized on silicon substrate using a thermal chemical vapor deposition (TCVD) system with a mixed gas flow of 1300 sccm H_2 and 1000 sccm C_2H_4 as the precursor at $750^\circ C$.^{41,42} Before synthesis, a silicon substrate with a 200 nm SiO_2 layer on top was cleaned with a standard process. Next, 1 nm Fe and 15 nm Al_2O_3 were coated on Si substrate using an atomic layer deposition (ALD) system, functioning as the catalyst and buffer layer, respectively. After the growth process, the VACNTs were placed into a furnace at $500^\circ C$ for 5 min under air ambient to provide a weak oxidation environment.⁴³ Subsequently, the VACNTs can be released from the Si substrate.

The preparation of the target substrate (PDMS/Cu/PET) starts from the cleaning of the PET substrate with a thickness of $95.6 \pm 0.3 \mu m$. A $1 \mu m$ Cu layer, which serves as a ground layer to block transmission of THz waves, was then deposited onto the PET substrate by an electron beam evaporation process. The PDMS solution and curing agent (ratio 10:1) mixture was then spin coated (Laurell-MODEL WS-650MA-23NPP) onto the Cu surface at 2000 rpm for 30 s to obtain a PDMS thickness of $65 \mu m$. Furthermore, the PDMS/Cu/PET substrate was placed into an oven at $110^\circ C$ for 15 mins.⁴⁴ After this curing process, the VACNTs on Si substrate were inverted upside down and pressed onto the PDMS/Cu/PET substrate for 10 min. Finally, the original Si substrate was peeled off and the VACNTs were successfully transferred to the PDMS/Cu/PET substrate.

Sample characterizations

The fabricated samples were characterized by a scanning electron microscopy (SEM), ZEISS Sigma VP, to obtain the geometric parameters, such as the length, diameter, and the uniformity of VACNTs. A custom-designed Raman spectroscopy system was used to investigate the morphology of VACNTs. This system contains a continuous wave ultra-

narrow linewidth laser (COHERENT Sapphire SF 488-50) as the source, providing an output power of 50 mW and a spectral resolution of 0.05 nm. The spectra of samples on Si substrate and PDMS/Cu/PET substrate were measured with a dwell time of 20 second at each point. The source was illuminated from the top at normal incidence, and the direction of E-field was perpendicular to the axial direction of VACNTs.

Terahertz Time-Domain Spectroscopy Measurement

A commercial terahertz time-domain spectrometer (Zomega-Z3) was employed to perform the reflection-mode measurements for the two samples. A 800 nm Ti:Sapphire laser with a pulse width of 100 fs was applied to excite a low-temperature grown GaAs photoconductive antenna for THz signal generation. The THz signal has a spectral coverage from 0.1 to 3.0 THz, and the peak dynamic range is about 70 dB at 0.7 THz. A 1 mm thick <110> ZnTe crystal was used as the THz detector for electro-optical sampling. The frequency-dependent amplitude and phase of THz signals were obtained via fast Fourier transform of the time-domain waveforms. A dry environment (humidity < 1.5%) was ensured by purging nitrogen into the chamber to reduce atmospheric attenuation.

For reflection-mode measurements at normal incidence, the incident THz waves were reflected by the sample, passed through a beam splitter and then detected by the ZnTe crystal. For oblique angle measurements, a theta-to-theta module was used to change the incident angle between 15° and 80°. The reflected THz signals were first collected by a retro-reflector, and then directed towards the ZnTe receiver for signal detection. This causes a longer optical path when compared with normal incidence situation, and thus results in a lower signal-to-noise ratio. A silver mirror was used as the reference to obtain the power reflectance of the samples.

Conclusions

In conclusion, we have experimentally demonstrated a flexible VACNT-based absorber that can work efficiently within the entire THz range. At normal incidence, strong and consistent absorptions were obtained for absorbers with different VACNT thicknesses, providing an average power absorptance of 0.989 and 0.993 within 0.1-3.0 THz, respectively. By oblique incidence experiments, it was confirmed that the proposed absorbers were not sensitive to the incident angle, and still have an average power absorptance of >0.97 for incident angles up to 60° for both samples. The flexibility of the device was further tested by wrapping the two devices around curved objects, obtaining almost identical absorption performances for bending angles up to 90° . After being bent for over 300 times, no significant degradation in absorption performance was observed. The overall thickness of the device is $\sim 360\text{ }\mu\text{m}$ ($t_{VACNT} = 300\text{ }\mu\text{m}$), which is only $1/8$ of the wavelength for the lowest evaluated frequency of 0.1 THz. Being incident angle- and polarization-insensitive, ultra-broadband, flexible, low cost and lightweight, the proposed device opens the possibility for electromagnetic interference shielding, radar cross section reduction and imaging applications in the future.

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Figure 8: Experimental results for bending test 2. Measured power absorbance between 0.1 and 2.5 THz for THz absorbers after different times of bending for (a) $t_{VACNT} = 300 \mu\text{m}$ sample and (b) $t_{VACNT} = 450 \mu\text{m}$ sample. (c) Average power absorbance for both samples as a function of times of bending.