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A Flexible and Stretchable Terahertz Imaging Sheet for Multi-View Visualization

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ABSTRACT

We have developed flexible and stretchable terahertz (THz) imaging devices based on carbon nanotube films that exhibit high absorption in a broadband frequency region. We report on multi-view THz imaging methods, which have enabled us to fully visualize both the whole outer and inner surface of various industrial products.

1 Introduction

Imaging technologies based on terahertz (THz) waves are promising for the use in non-destructive inspections due to their capabilities of relatively high penetration and fingerprint spectra of various materials [1,2]. Although most real objects have various three-dimensional curvatures, conventional THz imaging systems are mainly restricted to flat samples, hampering accurate measurements of such curved structures. To make THz sensing technologies more practical and easy-to-use, we have developed flexible and stretchable THz imaging sheets based on macroscopically bendable carbon nanotube (CNT) films [3-10]. We have thus demonstrated omnidirectional nondestructive THz inspections that are inaccessible with conventional solid-state THz imagers. The developed imagers have enabled us to examine the whole inner and outer surface of curved infrastructure equipment and various industrial products.

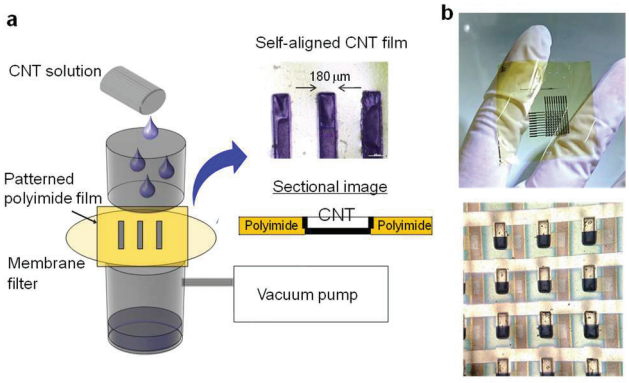

Fig. 1 (a) Schematic of the self-aligned filtration process of a free-standing CNT film array (b) Photograph of THz imaging patch sheets based on CNTs. Reprinted with permission from [8]. Copyright 2021, Wiley-VCH GmbH.

2 Experiment

We used a CNT film as a material for the flexible THz sensor owing to its advantages over conventional semiconductor materials, such as mechanical strength,

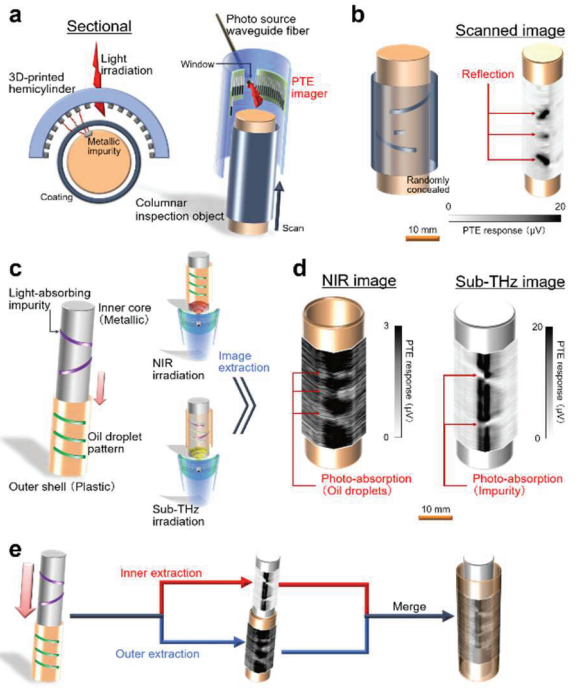

Fig. 2 (a) Schematic of the multi-view stereoscopic imager. (b) Non-destructive reflective multi-view imaging of a glass beverage bottle in the sub-THz (λ = 1.15 mm) frequency region in which metallic impurities were concealed by an opaque coating. (c) Hierarchical image extraction of a multi-layered columnar object with the reflective multi-view multi-frequency band imaging in sub-THz (λ = 1.15 mm) and NIR (λ = 870 nm) frequency regions. (d) Image extractions of the outer shell (NIR), and the inner core (sub-THz). (e) Image restoration of the multi-layered columnar object by covering the inner hierarchical image with the outer hierarchical one. Reprinted with permission from [9]. Copyright 2021, Springer Nature.

high absorption spectra in a broadband frequency range and high thermopower with the Seebeck coefficient of over 200 μV/K [3-7]. The detection mechanism of the flexible THz sensor is based on the photothermoelectric effect in the CNT films.

3 Results

3.1 Multi-view stereoscopic imager

Figure 2 (a) depicts schematic image of the multi-view THz imaging system. The outer surface of cylindrical objects was covered with the flexible THz imager that consisted of the CNT sensor array [9]. The THz waves irradiated from the outside were reflected on the curved surface of the inspection object, and then were detected by the each arrayed CNT sensor. Figure 2 (b) shows multi-view reflection THz images of a cylindrical mass-produced industrial product [9]. The observed THz image of the beverage bottle clearly shows the occurrence of strong reflection of the THz signals, thus revealing the existence of metallic impurities on the curved surface that were concealed by an opaque coating.

Further, by employing multi-frequency photo-monitoring, ranging between THz and near-infrared (NIR) bands, we were able to extract both the outer surface and inner surface features with the NIR and THz light, respectively (Fig. 2 c-e) [9].

3.2 Stretchable and deformable photo-sensor sheet

We have further developed a deformable patch containing CNTs and stretchable electrodes [10]. As an example of applications of this sensor sheet, Figure 3 presents experimental results for liquid quality monitoring. We wrapped the sensor sheet around the pipe, and found

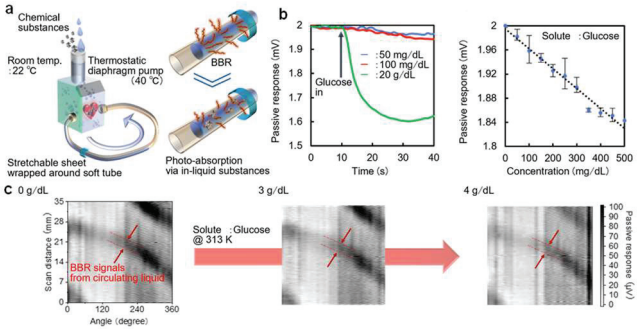

Fig. 3 (a) Schematic of the concept and measurement setup for non-sampling and label-free passive on-site dynamic photo-monitoring of in-liquid chemicals concentrations. (b) Passive responses of the CNT sensor with different glucose solution concentrations. (c) Comparison in passive images of concealed three-dimensional liquid flowing obtained by the CNT multi-view imager for different amounts of chemicals dissolution. Reprinted with permission from [10]. Copyright 2022, American Association for the Advancement of Science.

correlation between glucose concentration and generated photo-detected voltage. This indicates that the chemical content in the water flowing through the pipe was successfully monitored.

Current existing methods require the periodic collection of samples for testing, as well as the use of chemical reagents or labels. In contrast, the developed approach does not need sampling, chemical labels, or an external light source. We expect that this research can lead to non-destructive continuous monitoring, rather than during scheduled collections, and the on-site quality control of chemical factories or environmentally sensitive water sites.

4 Conclusions

We have developed THz video camera patch sheets based on self-aligned, suspended sensor array patterning, multi-view stereoscopic imagers, and stretchable and deformable photo-sensor sheets. As applications of these bendable THz imagers, we demonstrated nondestructive detection of impurities concealed inside coating and non-sampling and label-free chemical monitoring.

Because of high degree of flexibility, high durability, and low-cost mass-production capability, we can mount the present broadband bendable THz imaging sheet on objects regardless of their shapes, sizes, and locations, indicating the possibility of useful sensing components such as portable THz sensor, wearable THz sensor, and built-in THz sensor. We expect that this bendable THz imager will enlarge the adaptable range of THz imaging and remote sensing.

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References

[1] M. Tonouchi, “Cutting-edge terahertz technology”, Nature Photonics 1, 97 (2007).

[2] Y. Kawano, “Terahertz Sensing and Imaging Based on Nanostructured Semiconductors and Carbon Materials“, Laser & Photonics Reviews 6, 246 (2012).

[3] D. Suzuki, S. Oda, and Y. Kawano, “A flexible and wearable terahertz scanner”, Nature Photonics 10, 809-814 (2016).

[4] D. Suzuki, Y. Ochiai, Y. Nakagawa, Y. Kuwahara, T. Saito, and Y. Kawano, “Fermi-level-controlled semiconducting-separated carbon nanotube films for flexible terahertz imagers”, ACS Applied Nano

Materials 1, 2469–2475 (2018).
[5] D. Suzuki, Y. Ochiai, and Y. Kawano, “Thermal device design for a carbon nanotube terahertz camera”, ACS Omega 3, 3540–3547 (2018).
[6] D. Suzuki and Y. Kawano, “Flexible terahertz imaging systems with single-walled carbon nanotube films“, Carbon 162, 13-24 (2020).
[7] Kou Li, Daichi Suzuki, and Yukio Kawano, “Series Photothermoelectric Coupling Between Two Composite Materials for a Freely Attachable Broadband Imaging Sheet”, Advanced Photonics Research **2**, 2000095 (2021).
[8] Daichi Suzuki, Kou Li, Koji Ishibashi, and Yukio Kawano, “A terahertz video camera patch sheet with an adjustable design based on self - aligned, 2D, suspended sensor array patterning”, Advanced Functional Materials 31, 2008931 (2021).
[9] Kou Li, Ryoichi Yuasa, Ryogo Utaki, Meiling Sun, Yu Tokumoto, Daichi Suzuki, and Yukio Kawano, “Robot-assisted, source-camera-coupled multi-view broadband imagers for ubiquitous sensing platform”, Nature Communications 12, 3009 (2021).
[10] K. Li, T. Araki, R. Utaki, Y. Tokumoto, M. Sun, S. Yasui, N. Kurihira, Y. Kasai, D. Suzuki, R. Marteijn, J. D. Toonder, T. Sekitani, and Y. Kawano, “Stretchable broadband photo-sensor sheets for non-sampling, source and label-free chemical monitoring by simple deformable wrapping”, Science Advances 8, eabm4349 (2022).