Cantilever-based photoacoustic sensor for terahertz range

Erkki Ikonen*[a,b], Sucheta Sharma[a], Mohsen Ahmadi[c], Jussi Rossi[d], Markku Vainio[e], Zhipei Sun[c], and Andreas Steiger[f]

[a]Metrology Research Institute, Aalto University, Espoo, Finland; [b]VTT MIKES, VTT Technical Research Centre of Finland, Espoo, Finland; [c]Department of Electronics and Nanoengineering, Aalto University, Espoo, Finland; [d]Photonics Laboratory, Tampere University, Tampere, Finland; [e]Department of Chemistry, University of Helsinki, Helsinki, Finland; [f]Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany

ABSTRACT

Advantages of photoacoustic detection with a silicon cantilever microphone are demonstrated in the THz range. In our method, earlier membrane microphone is replaced with robust silicon cantilever microphone, which can tolerate high intensity of the input radiation in contrast to vulnerable membrane. The responsivity of the photoacoustic sensor was confirmed to be constant over almost six orders of magnitude of input power, which is not easy to achieve with any other detector of THz radiation. Another favorable feature of the photoacoustic sensor is its uniform spatial responsivity over areas of several millimeters in size. Finally, we measured nearly constant spectral responsivity of the photoacoustic sensor for the wavelength range of 0.3 µm to 200 µm.

Keywords: Photoacoustic sensor, THz radiation detection, linearity, damage threshold, flat spectral responsivity

1. INTRODUCTION

Research efforts in the THz detection technology have resulted in thermal, optical, and semiconductor-based detection processes.[1-5] Recent studies have shown the potential of optomechanical detection systems.[6-8] Golay cells are widely used detectors to be applied not only in the THz, but a considerably wide spectral range can be covered from ultraviolet (UV) to millimeter wavelengths.[1] However, the membrane-based pressure sensing method, as used in Golay cells, often has a restriction on the highest allowed power as the stress due to the gaseous pressure can cause mechanical damage to the membrane. Highest permissible power levels are typically in the µW range.[9,10] In some applications, a detection method with a large dynamic range and high damage threshold is required to avoid the need of multiple detection schemes for different power levels. Furthermore, a Golay cell detector may have nonuniform spatial responsivity for a THz laser beam because the detector structure is optimized for high responsivity.[9]

In our previous studies, we have reported a robust silicon cantilever-based pressure sensor for photoacoustic (PA) detection from UV to infrared region[11-13] and demonstrated its performance also for THz detection[8]. The window transmittance is a key parameter for the detection process to extend the spectral sensitivity towards the THz range. In addition, the sensing process of the detector depends on the radiation absorber material[11] and the pressure sensor of suitable dimensions[12]. A linear dynamic range of nearly six orders of magnitude can be achieved with PA detection, extending the detectable power range from nanowatt level to several milliwatts, or even up to 600 mW.[12,13] The absorber material can be damaged at power levels above 1 W. Nevertheless, the silicon cantilever is robust and can tolerate vibration amplitudes corresponding to high radiation power levels, if there would be a suitable absorber material for that purpose.

In this work, we summarize the features of our photoacoustic (PA) detection method regarding spatial uniformity and linearity of the responsivity. We show that with a carbon nanotube absorber material the responsivity is almost constant over a broad spectral range from UV to THz. Other significant features of the PA sensor are high sensitivity and high damage threshold.

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*erkki.ikonen@aalto.fi

2. METHODOLOGY

2.1 Cantilever-based photoacoustic sensor

The PA detection process is dependent on two main components: (a) radiation absorber and (b) silicon cantilever pressure sensor (Fig. 1). In the measurement, chopped radiation is absorbed by the absorber material, which results in periodic heating of gaseous medium inside the PA detector cell. Consequently, the pressure produced by the periodic heating of the gas makes the cantilever exhibit a mechanical response. The cantilever movement is finally sensed by a built-in interferometer to produce the PA signal. The key point in the presented PA detection method is the replacement of earlier membrane microphone with the robust silicon cantilever microphone, which can tolerate high intensity of the input radiation in contrast to vulnerable membranes.

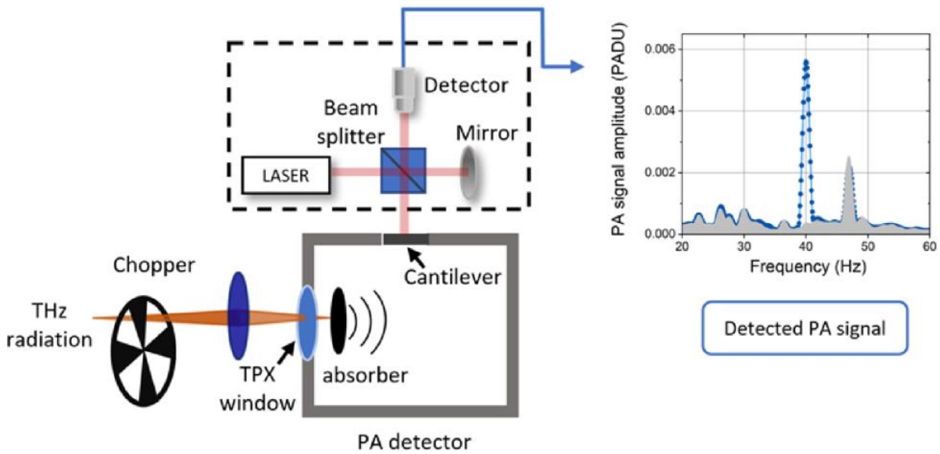

Figure 1. Simplified diagram of PA detector. The radiation absorber which receives the electromagnetic radiation is chopped at 40 Hz. The mechanical response of the cantilever sensor due to the generated gaseous pressure is detected with an interferometric method to produce the output PA signal. In the amplitude spectrum, the peak at 47 Hz is caused by acoustic noise in the laboratory room.

2.2 Absorber and window materials

We carried out THz experiments on two types of radiation absorbers: candle soot on aluminum produced at the tip of a flame and commercially available spray applied coating of randomly oriented carbon nanotube surface. Candle soot absorber shows higher detection responsivity than carbon nanotube from UV to infrared region, but the responsivity of soot material decreases as the incident radiation wavelength increases, while that of carbon nanotube absorber stays approximately constant.[11,13] In the THz range, the carbon nanotube absorber has a factor of two higher responsivity than the candle soot absorber.[8] For that reason the results in the following sections are mainly given for the carbon nanotube material.

The window transmittance of the detector plays an important role in estimating absorber responsivity at different wavelengths. For experiments in the THz and visible ranges, the window material is Polymethylpentene (TPX) while in the UV, visible and infrared ranges Potassium Bromide (KBr) windows are used. Window transmittances are from 85% to 91 % at all wavelengths where each of the windows was used.

3. RESULTS AND DISCUSSION

The PA sensor signal is produced by vibration of the cantilever due to pressure waves by periodic heating. Wavelength of the detected electromagnetic radiation only influences the efficiency by which radiation is converted to pressure waves. It is thus possible to make conclusions on the spatial uniformity, linearity, and sensitivity of the PA sensor responsivity at different wavelengths, when taking into account differences in spectral responsivity.

3.1 Spatial uniformity

Figure 2 shows results on responsivity measurements at different locations of the carbon nanotube absorber.[8] The responsivity is constant in Fig. 2(a) within 10% when most of the laser beam hits the black absorber material shown in Fig. 2(b). These results at 214 µm wavelength agree with our earlier measurements at 0.633 µm wavelength.[13]

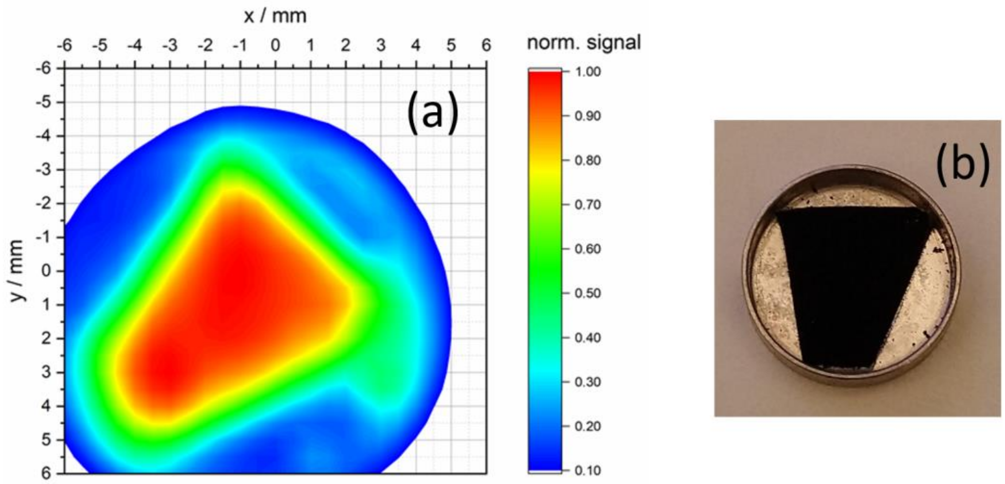

Figure 2. Spatial responsivity of the PA sensor (a) and photograph of the carbon nanotube absorber (b). The full width at half maximum of the focused Gaussian laser beam at 1.4 THz is 1.9 mm. The diameter of the absorber holder is 10 mm.

3.2 Linearity and sensitivity

The PA signal was measured as a function of incident electromagnetic power at several wavelengths. Results at 0.442 µm wavelength are shown in Fig. 3 where linearity over almost six orders of magnitude is demonstrated.[12] It is expected that similar linearity would be observed in the THz range where our earlier experiments were limited by the controlled adjustability of the THz laser power.

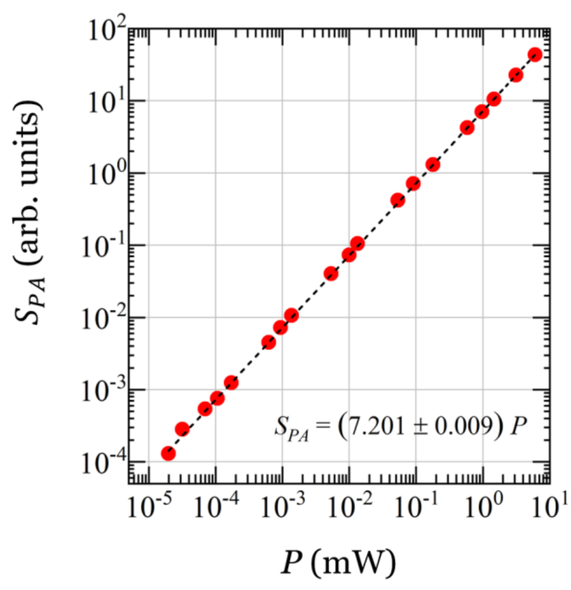

Figure 3. PA response with incident radiation power from ~15 nW to ~6 mW at 40 Hz chopping frequency at 0.442 µm wavelength.

The highest used power with the PA sensor was 12 mW at 1.4 THz which is much larger than typically used with Golay cell detectors. The noise-equivalent power is 160 nW/√Hz with almost five orders of magnitude linear dynamic range of THz radiation detection. The lowest detectable THz power of the PA detector with carbon nanotube absorber material is expected not to be as low as in the case of candle soot absorber in the visible wavelength range[13] because of a factor three lower responsivity. Furthermore, high ambient vibration level in the laboratory room with the THz laser increases the noise-equivalent power.

3.3 Spectral responsivity

Measurements of spectral responsivity of the PA sensor with carbon nanotube absorber were made in the wavelength range from 0.325 µm to 214 µm. Appropriate calibrated reference detectors were used at each wavelength.[14-16] Figure 4 shows the responsivity results scaled by the average of the responsivity in the range from 0.325 µm to 214 µm. The results are corrected for the differences in the TPX and KBr window transmittances. Spectral flatness of the responsivity in Fig. 4 is surprisingly good which facilitates comparison of PA signals at different wavelengths and with broadband radiation sources.

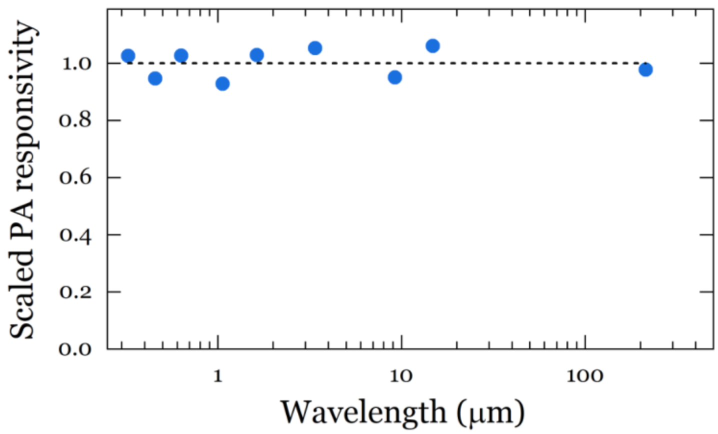

Figure 4. Relative spectral responsivity of carbon nanotube absorbers in the PA sensor.

4. SUMMARY

The photoacoustic detection method can be applied to measure electromagnetic radiation over a broad spectral range from UV to THz. Other advantages of the method, as compared with sensitive Golay cell detectors, are large dynamic range and high damage threshold for unintentionally coupled intense THz radiation. In addition, a spatial scan at 214 µm wavelength (1.4 THz) depicts a nearly uniform spatial responsivity on most of the area around the central region of the carbon nanotube surface. This study shows that a photoacoustic detector method has potential to serve as a sensitive detection unit for power measurement applications to cover a significantly broad spectral range including visible and THz wavelengths.

ACKNOWLEDGMENTS

We thank Gasera Ltd for designing the commercially available instrument parts employed in the experiments. This project is funded by the Academy of Finland Flagship Programme, Photonics Research and Innovation (PREIN), Finland, decision number: 320167. The project is also a part of Universal Electromagnetic Radiation Detector (UNIDET) research project, which is funded by the Academy of Finland, Finland, (Project numbers 314363 and 314364).

REFERENCES

[1] R. A. Lewis, "A review of terahertz detectors," J. Phys. D: Appl. Phys. 52, 433001 (2019).

[2] JS. Rieh, *Introduction to Terahertz Electronics* (Springer, 2021, Chap. 3).

[3] F. Sizov and A. Rogalski, "THz detectors," Prog. Quantum Electron. 34, 278-347 (2010).

[4] Y. Takida, K. Nawata, S. Suzuki, M. Asada, and H. Minamide, "Nonlinear optical detection of terahertz-wave radiation from resonant tunneling diodes," Opt. Express 25, 5389-5396 (2017).

[5] A. E. Yachmenev, R. A. Khabibullin, and D. S. Ponomarev, "Recent advances in THz detectors based on semiconductor structures with quantum confinement: a review," J. Phys. D: Appl. Phys. 55, 193001 (2022).

[6] C. Belacel, Y. Todorov, S. Barbieri, D. Gacemi, I. Favero, and C. Sirtori, "Optomechanical terahertz detection with single meta-atom resonator," Nat. Commun. 8, 1578 (2017).

[7] N. E. Glauvitz, R. A. Coutu, I. R. Medvedev, and D. T. Petkie, "Terahertz photoacoustic spectroscopy using an MEMS cantilever sensor," J. Microelectromech. Syst. 24, 216-223 (2015).

[8] S. Sharma, M. Ahmadi, J. Rossi, M. Vainio, Z. Sun, A. Steiger, and E. Ikonen, "Terahertz radiation detection with cantilever-based photoacoustic sensor," Opt. Express 30, 43417-43425 (2022).

[9] Tydex https://www.tydexoptics.com/ accessed on 19 August 2022.

[10] Microtech Instruments www.mtinstruments.com accessed on 19 August 2022.

[11] J. Rossi, J. Uotila, S. Sharma, T. Laurila, R. Teissier, A. Baranov, E. Ikonen, and M. Vainio, "Photoacoustic characteristics of carbon-based infrared absorbers," Photoacoustics 23, 100265 (2021).

[12] S. Sharma, T. Laurila, J. Rossi, J. Uotila, M. Vainio, F. Manoocheri, and E. Ikonen, "Electromagnetic radiation detection using cantilever-based photoacoustic effect: A method for realizing power detectors with broad spectral sensitivity and large dynamic range," Sens. Actuators, A 337, 113191 (2022).

[13] J. Rossi, J. Uotila, S. Sharma, T. Hieta, T. Laurila, R. Teissier, A. Baranov, E. Ikonen, and M. Vainio, "Optical power detector with broad spectral coverage, high detectivity, and large dynamic range," Opt. Lett. 47, 1689-1692 (2022).

[14] T. Donsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Petroff, E. Ikonen, "A primary standard of optical power based on induced-junction silicon photodiodes operated at room temperature," Metrologia 51, 197-202 (2014).

[15] K. Maham, A. Vaskuri, F. Manoocheri, E. Ikonen, "Calibration of near-infrared detectors using a wavelength tunable light source," Opt. Rev. 27, 183-189 (2020).

[16] A. Steiger, M. Kehrt, C. Monte, and R. Müller, "Traceable terahertz power measurement from 1 THz to 5 THz," Opt. Express 21, 14466–14473 (2013).