A HIGH SENSITIVITY MICROFLUIDIC CHANNEL ENABLED TERAHERTZ METAMATERIAL ABSORBER FOR SENSING AND DETECTION

Guangwu Duan[1], Jacob Schalch[2], Xiaoguang Zhao[1], Aobo Li[1], Richard Averitt[2], and Xin Zhang[1]
[1]Department of Mechanical Engineering, Boston University, Boston, Massachusetts, USA and
[2]Department of Physics, University of California, San Diego, La Jolla, California, USA

ABSTRACT

Metamaterials and metamaterial absorbers have been widely reported to be used in sensing and detection applications. Among them, metamaterial absorber is superior by its high-quality factor, and its high sensitivity to the change of the surrounding environment. However, the conventional metamaterials and metamaterial absorbers are configured with relatively thick substrates as their supporting structures with high permittivity, which compromises the sensitivity. Herein we utilize thin silicon nitride membrane as the supporting structure for the metamaterial layer to eliminate the high permittivity effect of the bulk substrate to achieve a much higher sensitivity. Moreover, we find the sensitivity can be further increased with thicker spacer thickness. The fabricated devices demonstrate a more than 3 times improvement in sensitivity compared with the state of art.

KEYWORDS

Metamaterial, Metamaterial absorber, Microfluidic channel, Thin film, High quality factor, Sensing and detection

INTRODUCTION

Metamaterials are engineered materials with artificial atomic structures to achieve extraordinary electromagnetic responses that do not exist in nature materials [1,2]. The electromagnetic response of metamaterials is largely determined by the geometry of the unit cells instead of the constituent materials. Therefore, by designing the size and shape of the unit cells, metamaterials can achieve tailored electromagnetic response [3-7], enabling various functionalities such as wave manipulation, perfect absorption, sensing and detection, among others. Recently, terahertz (THz) sensing has attracted tremendous interest, especially in the chemical detection and biological research, due to the THz fingerprints of chemicals and bio-molecules as well as the non-ionizing photon energy of THz waves [8,9]. Significant progress in THz sensing has been made with the adaptation of metamaterials into THz frequency regime. The transmission, reflection, and absorption spectra are usually employed as the indicator for the sensing and detection purposes [10]. Specifically, the presence of target molecules modifies the permittivity around the unit cells of metamaterials, causing resonance (frequency and amplitude) change to the spectra. By correlating the resonance change with the concentration of the target molecules, one can achieve the quantitative relationship, thereby detecting the presence of the chemical or measuring the concentration of it [11].

In some early works, conventional metamaterials were employed for the sensing applications. By depositing a thin layer of analyte or micro-particles interest on the unit cells, one can change the equivalent capacitance and/or resistance of the resonators, resulting in a resonant frequency shift and/or amplitude change [12]. The metamaterials can be configured into metamaterial absorbers with a three-layered configuration, i.e. a metamaterial-spacer-metal ground configuration, with much higher quality factors and larger response changes, potentiating a higher sensitivity for sensing and detection applications [13]. As a manipulation strategy with high precision, microfluidic channels can be integrated with either metamaterials or metamaterial absorbers to form a functional sensing device [11]. For the metamaterial absorber integration, the microfluidic channel can be configured at the front side of the metamaterial layer to achieve a channel-metamaterial-spacer-metal configuration, or the spacer material can be replaced by a channel, through which the target fluid can flow. For both configurations, channel caps must be employed as the testing window and the top cover of microfluidic channels. The impedance mismatch between free space and channel caps can cause significant power loss due to the reflection at the interface. Moreover, when the thickness of the cap is $n/2 + 1/4$ (n is an integer ≥ 0) times of the incident wavelength, multiple reflections inside cap layer can create reflection minima. Overlapping with the absorption spectra of metamaterial absorbers, the reflection minima can significantly compromise the detection accuracy. In this paper, we designed and fabricated a metamaterial absorber with a "free-standing" metamaterial layer on an ultra-thin (0.4 μm) silicon nitride (SiN_x) membrane. The "free-standing" metamaterial layer was integrated with a microfluidic channel and a ground plane to form a metamaterial absorber sensing device with fluidic media as spacer materials. By introducing the "free-standing" metamaterial layer, our design can remove the high effective permittivity effect. More importantly, we found that our design features a much larger absorption peak frequency shift and an extraordinary high quality factor. These features can be employed to dramatically increase the performance of sensing devices based on metamaterial absorbers.

SYSTEM DESIGN

Figure 1 shows the schematic drawing of the design. A "free-standing" metamaterial layer, with split ring resonators as unit cells and SiN_x as supporting membrane, was employed as the top layer of the metamaterial absorber. It also serves as the testing window for the incident THz pulses. The depth and shape of the microfluidic channel was defined by the SU8 layer, which was patterned on a ground plane. The in-channel media, functioning as the dielectric spacer, can be altered by injecting different fluidic analytes.

The utilization of a "free-standing" metamaterial layer enables a higher sensitivity (defined as the absorption peak frequency shift divided by the change of the in-channel permittivity). Numerical simulation was employed to study the response using frequency domain solver in CST Microwave Studio 2017.

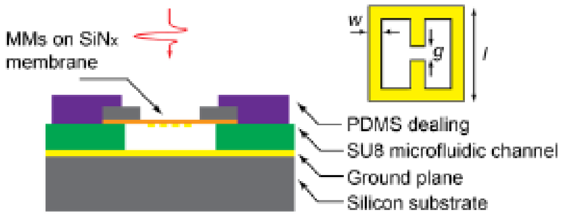

Figure 1. Schematic drawing of the microfluidic channel with a metamaterial absorber. The inset shows the unit cell geometries of the metamaterials with w = 5 µm, g = 8 µm, l = 50 µm. The periodicity of the unit cells is 60 µm.

We compared the absorption peak frequency shift of the metamaterial absorbers with a "free-standing" metamaterial layer, and metamaterials on quartz substrate [11]. All metallic portions were modeled as gold with conductivity of 4.56×10^7 S/m. The SiN_x membrane and the quartz substrate were modeled as lossy dielectrics with relative permittivity of $7.6 \times (1 + i0.0053)$ and $3.75 \times (1 + i0.0004)$, respectively, with their thicknesses labeled in Figure 2. Spacer thicknesses were optimized to achieve more than 90% absorption at the absorption peak frequency. The simulated absorption spectra are plotted in Figure 2 for different in-channel spacer permittivities.

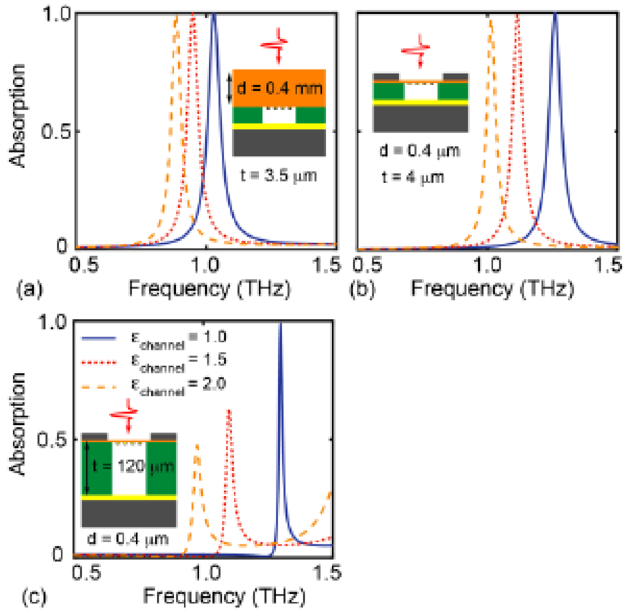

Figure 2. Simulated absorption spectra of metamaterial absorbers with different in-channel spacer permittivity for (a) metamaterials on quartz with a shallow channel, (b) "free-standing" metamaterials with a shallow channel, and (c) "free-standing" metamaterials with a deep channel. d and t denote the thickness of the supporting materials of metamaterial layers and the depth of the microfluidic channels, respectively.

The design with a "free-standing" metamaterial layer (Figure 2b) demonstrated more than 1.67 times of frequency shift compared to the design with a quartz substrate (Figure 2a). The increase in sensitivity can be explained with the lower base capacitance of the "free-standing" metamaterial layer due to the ultra-thin supporting membrane [14]. Figure 2c depicts the absorption spectra of the metamaterial absorber with a "free-standing" metamaterial layer and a deep microfluidic channel. The quality factor and the sensitivity demonstrate a marked increase due to the increased channel depth.

The increase in the quality factor can be understood qualitatively. The stored energy consists of two parts. One is due to the electric and magnetic field generated by the resonance of the metamaterial layer. The other is due to the Fabry-Perot-like resonance inside the cavity formed by the metamaterial layer and the ground plane. With a thin spacer thickness (4 µm) the energy storage is mostly due to the resonance of the metamaterial layer. However, with the increase in the spacer thickness, the Fabry-Perot-like resonance can gradually build up another cavity resonant mode with the round-way phase delay inside the spacer approaching multiple times of 2π. The Fabry-Perot-like resonance provides another pathway for energy storage, which, together with the energy storage due to the resonance of the metamaterials, significantly increases the total energy deposition inside the metamaterial absorber. Nevertheless, the energy loss due to power consumption (determined by the ohmic loss of the metamaterial layer which keeps constant at one frequency) and energy radiation (determined by the characteristic impedance of free space) remain constant [15]. As a result, the quality factor of the metamaterial absorber increases dramatically with the increase in the spacer thickness.

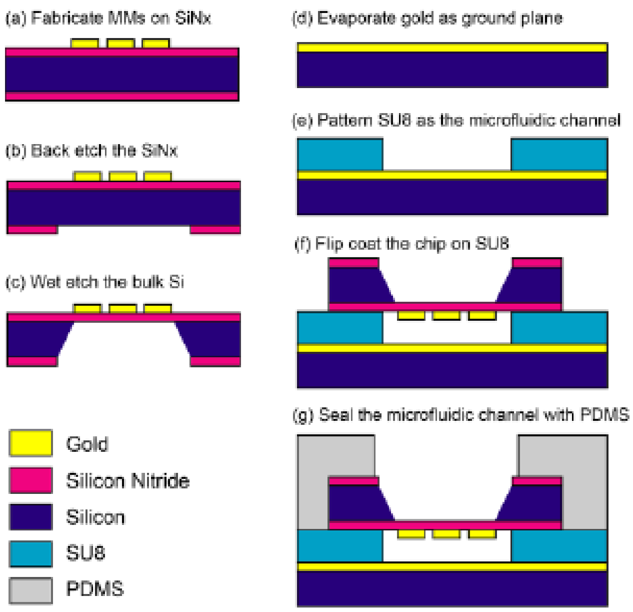

Figure 3. Fabrication process of the device. Two wafers were employed for the fabrication, one as the metamaterial window, the other as the ground plane and microfluidic channel. The two wafers were bonded with PDMS to seal the microfluidic channel.

EXPERIMENT AND RESULTS

The proposed metamaterial absorber was implemented with MEMS fabrication process as illustrated in Figures 3. A double-side SiN_x (0.4 µm-thick) coated wafer was employed to fabricate the metamaterial layer. Photolithography was used to define the geometry of metamaterials on the front side, followed by an e-beam evaporation deposition (10 nm chromium, 150 nm gold) and a liftoff process to fabricate the metamaterial structures. Etching windows were then defined with photolithography and plasma etching at the back side of the wafer. Eventually wet etching was employed to etch the bulk silicon, leaving only the "free-standing" metamaterials. The ground plane (10 nm chromium, 150 nm gold, 10 nm chromium) was fabricated through e-beam evaporation on a second wafer. Microfluidic channel was patterned with SU8 using photolithography. The depth of the channel was defined by the thickness of SU8 (120 µm). PDMS was molded, punctured, and treated with triethoxysilane (3-Aminopropyl) as the sealing material. Finally, the metamaterial chip was flip-chip-aligned with the channel chip, and the they were bonded together with PDMS by applying heat and pressure to seal the microfluidic channel [16]. The fabricated device is shown in Figure 4.

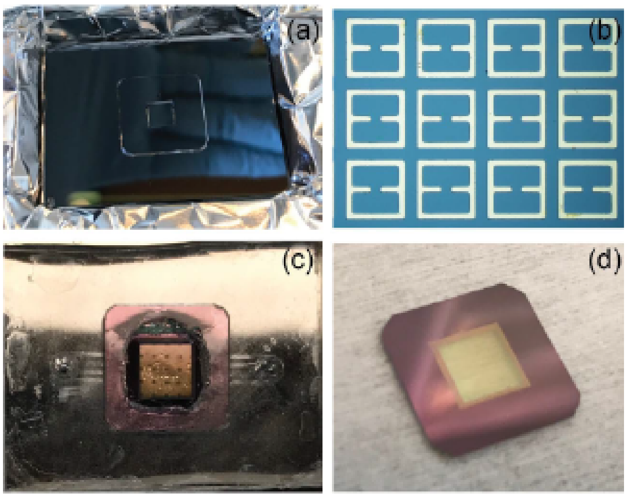

Figure 4. (a) the molded PDMS for the bonding. (b) the microscopic image of the metamaterials. (c) the bonded microfluidic channel enabled metamaterial absorber. (d) the image of the metamaterial window.

The fabricated devices were tested with THz time domain spectroscopy. The absorption spectra were measured with different fluidics inside the microfluidic channel. The measurements are illustrated in Figure 5. The absorption spectrum was first measured with air as the dielectric spacer, showing an absorption peak at 1.33 THz. Then methanol was injected with a syringe to fill the microfluidic channel, and the absorption spectrum was measured. Correspondingly, the absorption peak frequency shifted to 0.78 THz. The absorption spectra were also simulated with the in-channel permittivity of air (1) and methanol (3 + i0.8). The simulation results show high degree of agreement with the measurements as plotted in Figure 6. Compared with the reported results with a quartz cap [11], our design demonstrates more than 3 times improvement in sensitivity.

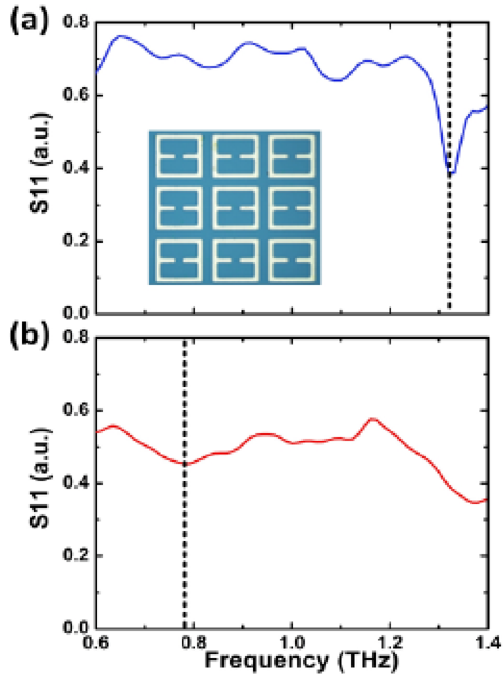

Figure 5. The measured reflection coefficient of the fabricated device with THz Time Domain spectroscopy for (a) air in channel and (b) methanol in channel. The dashed lines indicate the absorption peak frequency shift (0.55 THz). Inset: The microscopy image of the metamaterials.

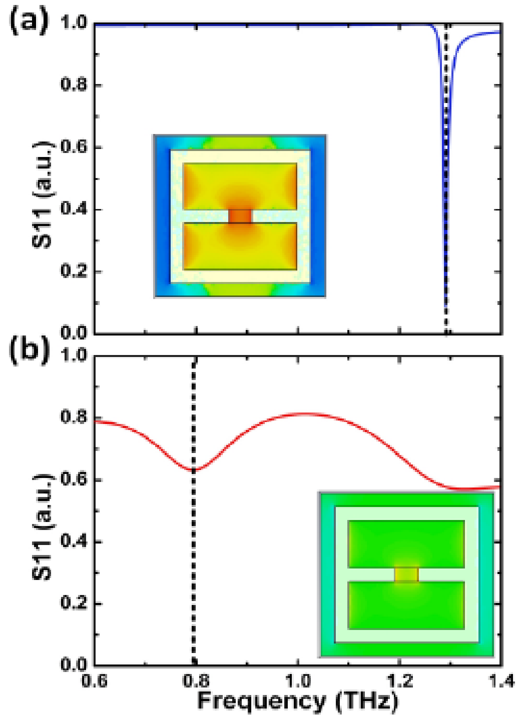

Figure 6. The simulated reflection coefficient of the fabricated device with (a) air and (b) methanol in channel. Insets: electric fields at resonance frequencies. The simulation results agree with the measurement results very well.

CONCLUSIONS

In conclusion, we designed, fabricated, and tested a microfluidic channel enabled metamaterial absorber featuring an enhanced sensitivity and an increased quality factor. The sensitivity enhancement is due to the "free-standing" metamaterial layer and the large channel depth. With the increase in the depth of the channel, another Fabry-Perot resonant mode can be introduced to increase the energy deposition inside the metamaterial absorber resulting in a significant increase in the quality factor. Moreover, the increase in the channel height also decreases the coupling between the absorption peak frequency and the channel depth yielding a more robust device. Our design can be readily employed to improve the performance of metamaterial-absorber-based sensing devices.

ACKNOWLEDGEMENTS

We acknowledge the support from the National Science Foundation (NSF) (No. ECCS-1810252) and the Army Research Office (ARO) (No. W911NF-16-1-0361). We thank the Boston University Photonics Center for technical support.

REFERANCES

[1] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite Medium with Simultaneously Negative Permeability and Permittivity", *Physical Review Letter*, vol. 84, pp. 4184-4187, 2008.

[2] D. R. Smith, J. B. Pendry, M. C. K. Wiltshire, "Metamaterials and Negative Refractive Index", *Science*, vol. 305, pp. 106-113, 2004.

[3] X. Zhao, K. Fan, J. Zhang, G. R. Keiser, G. Duan, R. D. Averitt, and X. Zhang, "Voltage-tunable Dual-layer Terahertz Metamaterials", *Microsystem & Nanoengineering – Nature*, vol. 2, pp. 16025, 2016.

[4] X. Zhao, J. Schalch, J. Zhang, H. R. Seren, G. Duan, R. D. Averitt, and X. Zhang, "Electromechanically Tunable Metasurface Transmission Waveplate at Terahertz Frequencies", *Optica*, vol. 5, pp. 303-310, 2018.

[5] X. Zhao, G. Duan, A. Li, C. Chen, and X. Zhang, "Integrating Microsystems with Metamaterials Towards Metadevices", *Microsystem & Nanoengineering – Nature*, vol. 5, pp. 5, 2019.

[6] N. I. Landy, and D. R. Smith, "A Full-parameter Unidirectional Metamaterial Cloak for Microwaves", *Nature Material*, vol. 12, pp. 25-28, 2013.

[7] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect Metamaterial Absorber", *Physical Review Letters*, vol. 100, pp. 207402, 2008.

[8] J. Barber, D. E. Hooks, D. J. Funk, R. D. Averitt, A. J. Taylor, and D. Babikov, "Temperature-dependent Far-infrared Spectra of Single Crystals of High Explosives Using Terahertz Time-Domain Spectroscopy", *The Journal of Physical Chemistry A*, vol. 109, pp. 3501-3505, 2003.

[9] J. A. Zeitler, K. Kogermann, J. Rantanen, T. Rades, P. F. Taday, M. Pepper, J. Aaltonen, and C. J. Strachan, "Drug Hydrate Systems and Dehydration Processes Studied by Terahertz Pulsed Spectroscopy", *International Journal of Pharmaceutics*, vol. 334, pp. 78-84, 2007.

[10] G. Duan, X. Zhao, H. R. Seren, C. Chen, A. Li, and X. Zhang, "An Air-spacer Terahertz Metamaterial Perfect Absorber for Sensing and Detection Application", *Transducer 2017*, pp. 1999-2002, 2017.

[11] X. Hu, G. Xu, L. Wen, H. Wang, Y. Zhao, Y. Zhang, D. R. S. Cumming, and Q. Chen, "Metamaterial Absorber Integrated Microfluidic Terahertz Sensors", *Laser & Photonics Reviews*, vol. 10, pp. 962-969, 2016.

[12] S. J. Park, S. A. N. Yoon, and Y. H. Ahn, "Dielectric Constant Measurements of Thin Films and Liquids Using Terahertz Metamaterials", *RSC Advances*, vol. 6, pp. 69381-69386, 2016.

[13] G. Duan, J. Schalch, X. Zhao, J. Zhang, R. D. Averitt, and X. Zhang, "An Air-spaced Terahertz Metamaterial Perfect Absorber", *Sensors and Actuators A: Physical*, vol. 280, pp. 303-308, 2018.

[14] H. Tao, A. C. Strikwerda, M. Liu, J. P. Mondia, E. Ekmekci, K. Fan, D. L. Kaplan, W. J. Padilla, X. Zhang, R. D. Averitt, and F. G. Omenetto, "Performance Enhancement of Terahertz Metamaterials on Ultrathin Substrates for Sensing Applications", *Applied Physics Letters*, vol. 97, pp. 261909, 2010.

[15] G. Duan, J. Schalch, X. Zhao, A. Li, C. Chen, R. D. Averitt, and X. Zhang, "A Survey of Theoretical Models for Terahertz Electromagnetic Metamaterial Absorbers", *Sensor and Actuators A: Physical*, vol. 287, pp. 21-28, 2019.

[16] Y. Ren, S. H. Huang, S. Mosser, M. O. Heuschkel, A. Bertsch, P. C. Fraering, J. J. Chen, and P. Renaud, "A Simple and Reliable PDMS and SU-8 Irreversible Bonding Method and Its Application on a Microfluidic-MEA Device for Neuroscience Research", *Micromachines*, vol. 6, pp. 1923-1934, 2015.

CONTACT

*X. Zhang, tel: +1-617-358-2702; xinz@bu.edu