Supplementary Information

Optically Modulated Ultra-Broadband All-Silicon Metamaterial Terahertz Absorbers

Xiaoguang Zhao1,#, Yue Wang2,#, Jacob Schalch1, Guangwu Duan1, Kevin Cremin3, Jingdi Zhang3, Chunxu Chen1, Richard D. Averitt3,*, and Xin Zhang1,*

1 Department of Mechanical Engineering, Boston University, 110 Cummington Mall, Boston, Massachusetts 02215, USA
2 Department of Applied Physics, Xi’an University of Technology, South Jinhua Road, Xi’an, Shanxi 710048, China
3 Department of Physics, University of California, San Diego, 9500 Gilman Dr., La Jolla, California 92093, USA
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Corresponding authors: raveritt@ucsd.edu and xinz@bu.edu
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These authors contributed equally.

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1. Dimensions of the metamaterial perfect absorber

The schematic of the unit cell of the all-silicon metamaterial perfect absorber (MPA) is shown in Fig. S1 and the dimensions are listed in Table S1.

Figure S1. (a) Schematic of the unit cell of the THz metamaterial perfect absorber on silicon substrate; (b) the top view, and (c) the side view. The geometric parameters of the designed structure are shown in Table S1.

| Table S1. The dimensional parameters of the MPA unit cell. |
|-------------------------------------------------------------|
| \( p \) (\( \mu m \)) | \( a \) (\( \mu m \)) | \( t \) (\( \mu m \)) | \( d \) (\( \mu m \)) | \( b \) (\( \mu m \)) | \( l \) (\( \mu m \)) | \( h \) (\( \mu m \)) |
| Designed value | 140 | 110 | 250 | 10 | 82 | 12 | 53 |

2. Effect of the cavities in the bars of the H-shaped unit cell

Figure S2 shows the simulation results for the MPA unit cells with (blue) and without (red) holes in the bars of the H-shape. The bandwidth of \(~900\) GHz for 90% absorbance is achieved in the vicinity of \(0.97\) THz with holes in the H-shape, and the bandwidth is \(~870\) GHz for the MPA without holes in the unit cells. In addition, the absorbance of the MPA with holes is stronger than the one without holes at the higher frequencies. As a result, we employed the H-shaped unit cells with holes in the side bars with increased absorption bandwidth.

Figure S2. Absorbance spectrum of the all-silicon MPA without (blue) and with (red) holes in the H-shaped unit cell side bars.
3. Effects of the metamaterial geometry
According to our simulation results shown in Fig. S3, the height of the metamaterial layer \((h)\) and side width \((a)\) of the “H-shaped” unit cell are crucial to determine the resonance frequencies of the absorber. The dimensions of the cavities, including \(b\) and \(l\), affect the second resonance frequency, as shown in Figs. S3(c) and S3(d).

![Simulated absorbance spectra](image)

**Figure S3.** Simulated absorbance spectra of the device as a function of (a) varying depth of \(h\), (b) size of pattern cell \(a\), (c) length of \(b\) and, (d) width of \(l\) for rectangular cavities when the carrier density is \(n_d = 0.03 \times 10^{18}\) cm\(^{-3}\).

4. Resonance mode of the standalone metamaterial layer at the resonance frequency

![Electric and magnetic field distribution](image)

**Figure S4.** Electric (left) and magnetic (right) field distribution of the standalone MM layer at the resonance frequency, i.e. 1.4 THz. It is a TM resonance mode.
5. Properties of the silicon used in the design and simulation

Figure S5. (a) Electromagnetic properties of silicon used in the MPA. (b) The simulated reflectance (R), transmittance (T), and absorbance (A) of a silicon substrate with thickness of 250 μm.

6. Absorption spectrum depending on the incident angle

Figure S6 shows the absorbance of the MPA for different incident angles for a transverse electric (TE) polarization, i.e. the electric component along x-axis shown in Fig. 1 in the main text. The device is nearly insensitive to the incident angle when it is less than 40° in terms of changes in the resonance frequency and peak absorbance. The bandwidth for 90% absorbance decreases slightly as the incident angle increases. When the incident angle is larger than 40°, the overall absorbance quickly decreases.

Figure. S6 Absorbance spectra with different incident angles for transverse electric (TE) polarization.
7. Distribution of the carrier density under optical excitation

When optical pump light impinges on the MPA, the fluence decays exponentially due to absorption according to the Beer-Lambert law. The carrier density is shown in Fig. S7 for different pump fluences as calculated by Eq. (5) in the main text. We used the layered MPA model to match the optical pump and THz probe experimental results in simulations. The carrier densities of each layer, which were used in the simulations to match the experimental results, are listed in Table S2. We plot these numbers as well as the theoretical predicted carrier density distribution in Fig. S4 and achieved a good agreement. This indicates that the carrier density distribution used in our simulation is reasonable.

![Figure S7. The calculated carrier density (curves) and carrier density used in each layer of the layered MPA numerical model (bars) to match the simulation results with the experimental results.](image-url)
Table S2. The carrier density of the layers under different pump fluences.

| Pump fluence (µJ/cm²) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------------------------|----|----|----|----|----|----|----|----|----|----|
| 0                      | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 25                     | 0.10 | 0.10 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 50                     | 0.20 | 0.20 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 100                    | 0.45 | 0.30 | 0.20 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 200                    | 0.85 | 0.56 | 0.30 | 0.21 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 400                    | 1.67 | 1.0  | 0.63 | 0.38 | 0.25 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 800                    | 3.27 | 2.05 | 1.25 | 0.75 | 0.45 | 0.07 | 0.03 | 0.03 | 0.03 | 0.03 |
| 1600                   | 6.5  | 4.2  | 2.38 | 1.39 | 0.85 | 0.58 | 0.30 | 0.18 | 0.03 | 0.03 |
| 4000                   | 16.0 | 12.0 | 7.5  | 6.0  | 4.5  | 3.0  | 0.3  | 0.2  | 0.18 | 0.03 |

8. Experimental setup for characterization of the MPA

![Figure S8](image-url) (a) Schematic of terahertz time domain spectroscopy (TDS) experiment. (b) Schematic of the optical pump THz probe (OPTP) spectroscopy experiment.

9. Comparison with other reported experimental results of all-silicon THz metamaterial perfect absorbers

Table S3. Comparison with other reported experimental results of all silicon THz MPA

|                  | Peak absorbance | Bandwidth @ >90% absorbance | Tunability |
|------------------|-----------------|-------------------------------|------------|
| Ref. [S1]        | 98.5%           | ~290 GHz                      | No         |
| Ref. [S2]        | 100%            | ~2200 GHz                     | No         |
| Ref. [S3]        | 100%            | ~2000 GHz                     | No         |
| Ref. [S4]        | 97.5%           | ~20 GHz                       | Yes        |
| **Our work**     | **100%**        | **~913 GHz**                  | **Yes**    |

We achieved perfect absorption in the terahertz frequencies across a bandwidth of ~913GHz with absorbance higher than 90% in our work. More importantly, we demonstrated the optically tunable response of the broadband absorber and understand the tuning mechanism.
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