Metal-insulator-metal waveguide metamaterial absorber: Theory and experiment

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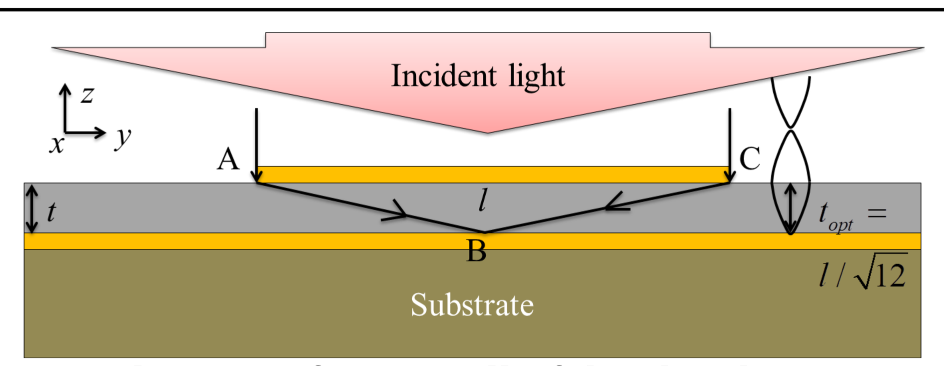
Abstract

Wavelength-selective plasmonic and metamaterial perfect absorbers have been studied extensively for various applications including infra-red (IR) bolometers, thermal imaging, thermal emitters, plasmonic sensing, and solar cells . We present an analytical model of metamaterial absorber based on metal-insulator-metal waveguide theory, supported strongly by experiments and numerical simulations. It follows the design principles of a typical metamaterial absorber which consists of surface patterns of periodic metallic squares, a dielectric spacer and a metallic ground plane. The analytical theory we developed calculates wavelengths for the resonance modes and can explain all the experimental results adequately. Thus, the theory presented here gives outstanding insight to the underlying physics of metamaterial absorbers.

Experimental measurements on single cell of such absorber is done using synchrotron FTIR microscopy in the mid-IR region. Far IR measurements are done using a BOMEM DA8 FTIR spectrometer.

Theoretical considerations



Schematic diagram of a unit cell of the absorber.

The path difference between the points A and C is

$$\Delta = 2n\sqrt{t^2 + l^2/4}$$

The phase difference including -π for reflection from metal is

$$\phi = \frac{2\pi n \Delta}{\lambda} - \pi$$

Using the condition that $\cos\phi = 1$ for standing waves formation

$$\lambda = \frac{4n}{2m+1}\sqrt{(t^2 + l^2/4)}$$

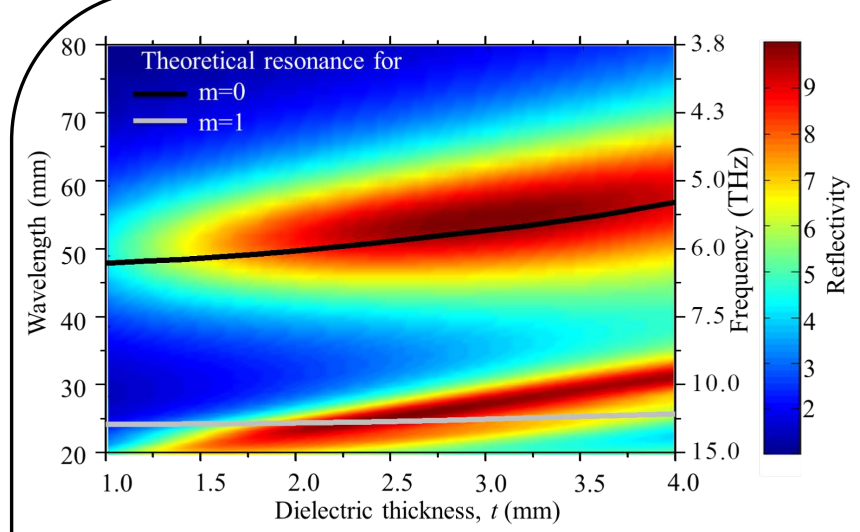
For m=0, 1, 2…

$$\lambda_0 = 4n\sqrt{(t^2 + l^2/4)}$$

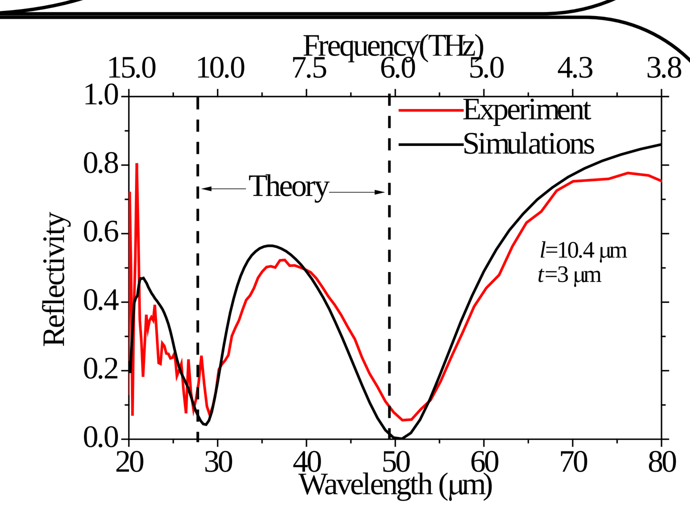
For m=0

$$\lambda_1 = \frac{4n}{3}\sqrt{(t^2 + l^2/4)}$$

For m=1

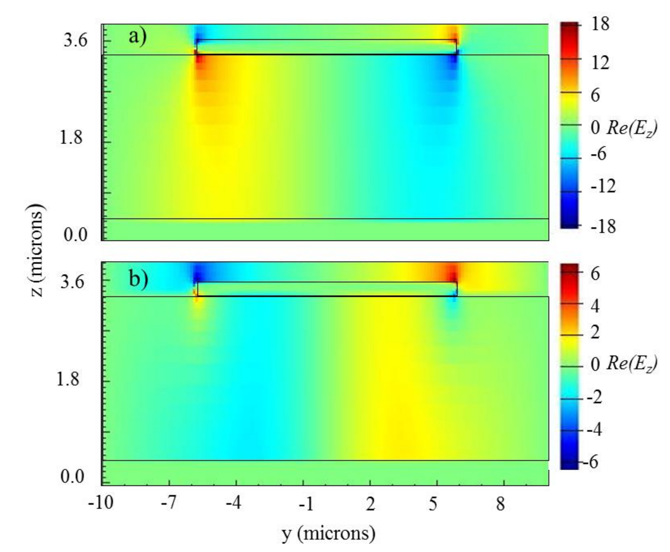


Colormap shows simulated reflectivity as a function of dielectric thickness and wavelength for the zeroth order and 1st order resonances for l=11.7 microns and period 20 microns

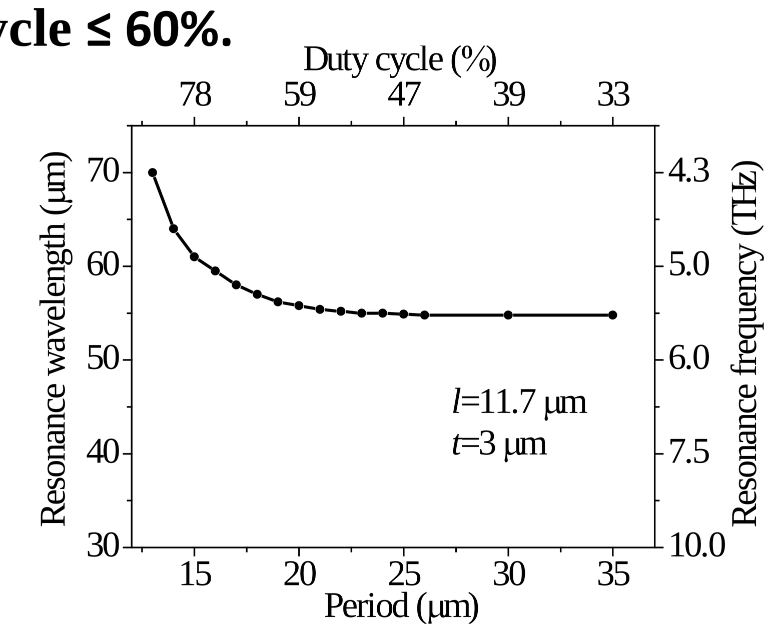


Theoretical, experimental and simulated reflectivity spectra for l=11.7microns, t=3 microns and period of 20 microns.

The squares can be considered as isolated and non-interacting when duty cycle ≤ 60%.



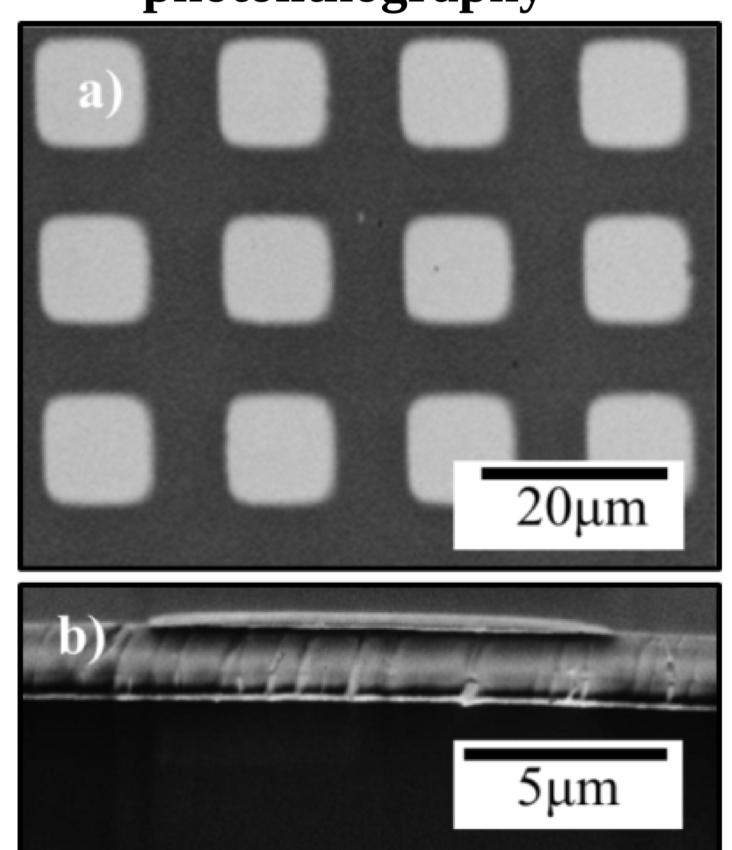
Simulated Colormap shows *Re(Ez)* for the 0th order and 1st order resonances for absorber with l=11.7 microns , t=3 microns and period 20 microns.



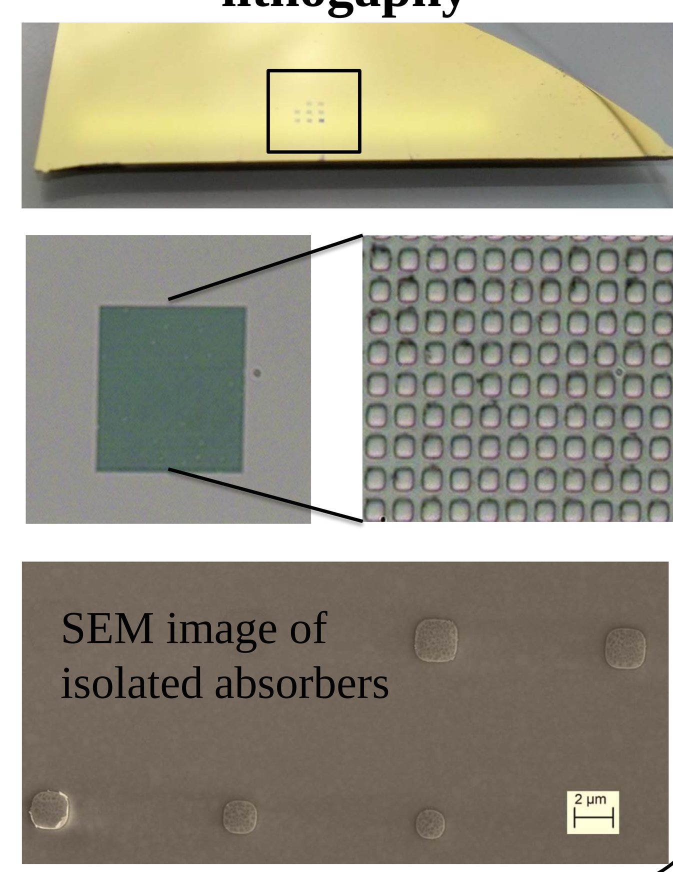
Simulated resonance wavelength for the 0th order resonance as a function of period of the squares. l=11.7 microns and t=3 microns, respectively

Fabrication

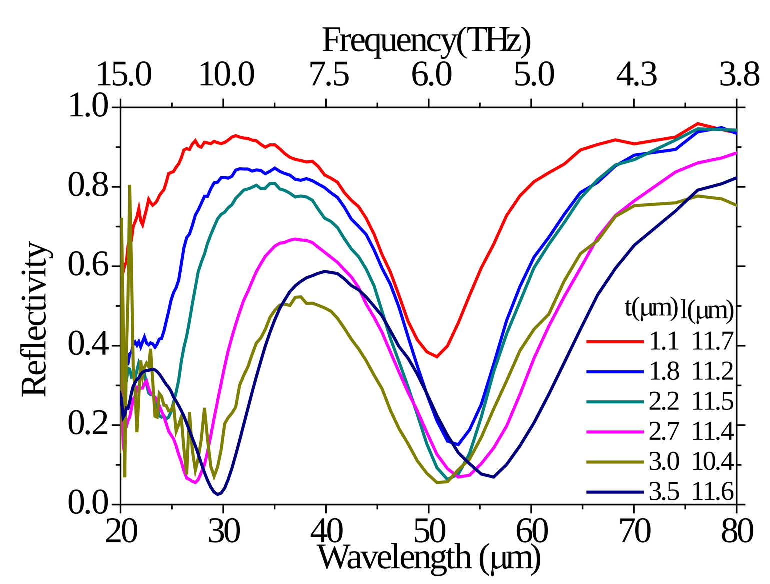
Far IR (THz) samples by photolithography



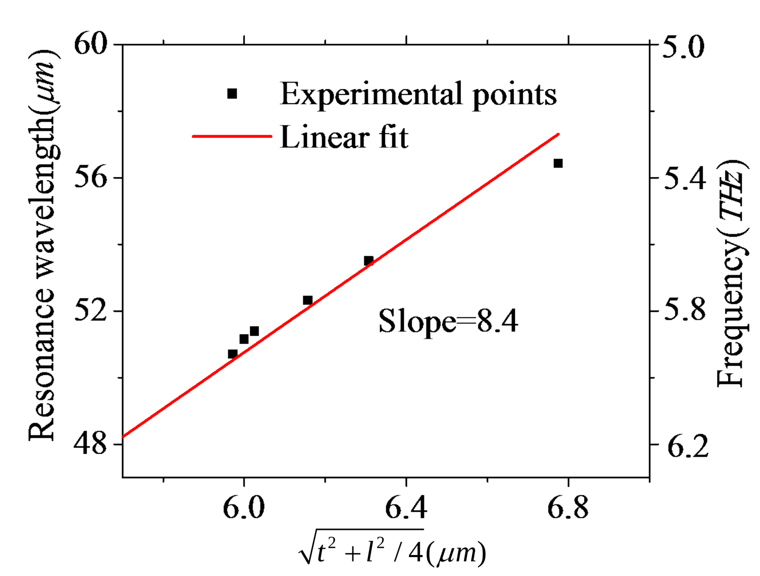
Mid-IR samples by ebeam lithogaphy



Results for far IR (THz) measurements



Experimental reflectivity spectra for samples with varying thickness t of SiO_2. Square size l of the squares varies sample to sample up to 10%



Experimental resonance wavelength as a function of for the 0th order resonance. Red line represents a linear fit of the data points which passes through the origin.

The calculated refractive index for the SiO_2 dielectric from the linear fit is n=2.2 which is close to previously reported value of 2.1 (at 50 microns wavelength).

Results for mid-IR measurements by synchrotron FTIR imaging

Image of a one-cell-metamaterial absorber with l=2.14 microns, t=0.1 microns and of infinite periodicity in a) optical microscope, b) SEM and c) synchrotron FTIR microscope d) Reflectivity spectra of single cell metamaterial absorber at 6.3 microns.

Calculated resonances are indicated by vertical dashed lines.

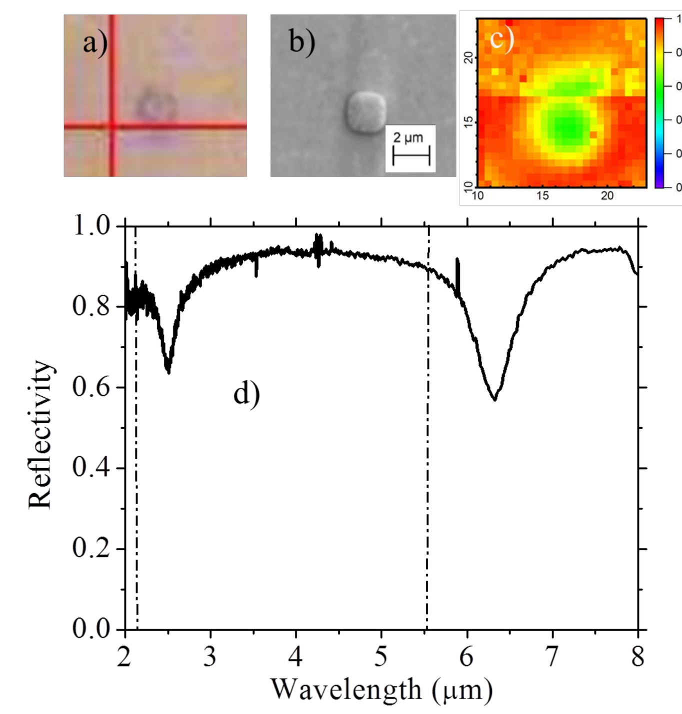


Image of a periodic arrays of the absorber with l=2.2 microns, t=0.1 microns and period, p=3.2 microns in a) SEM and b) synchrotron FTIR microscope c) Reflectivity spectra of the periodic square arrays

There is negligible effect of neighboring squares on the resonance wavelength which verifies our theory .

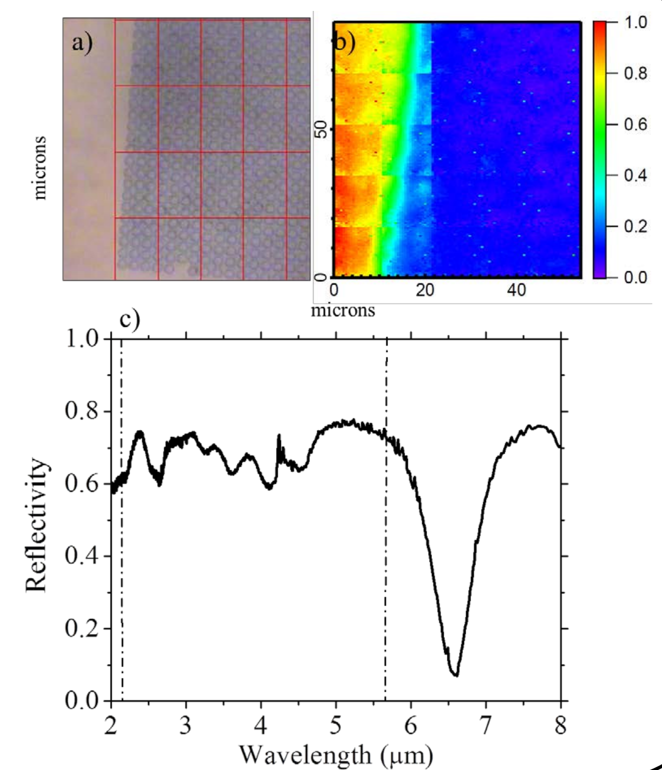
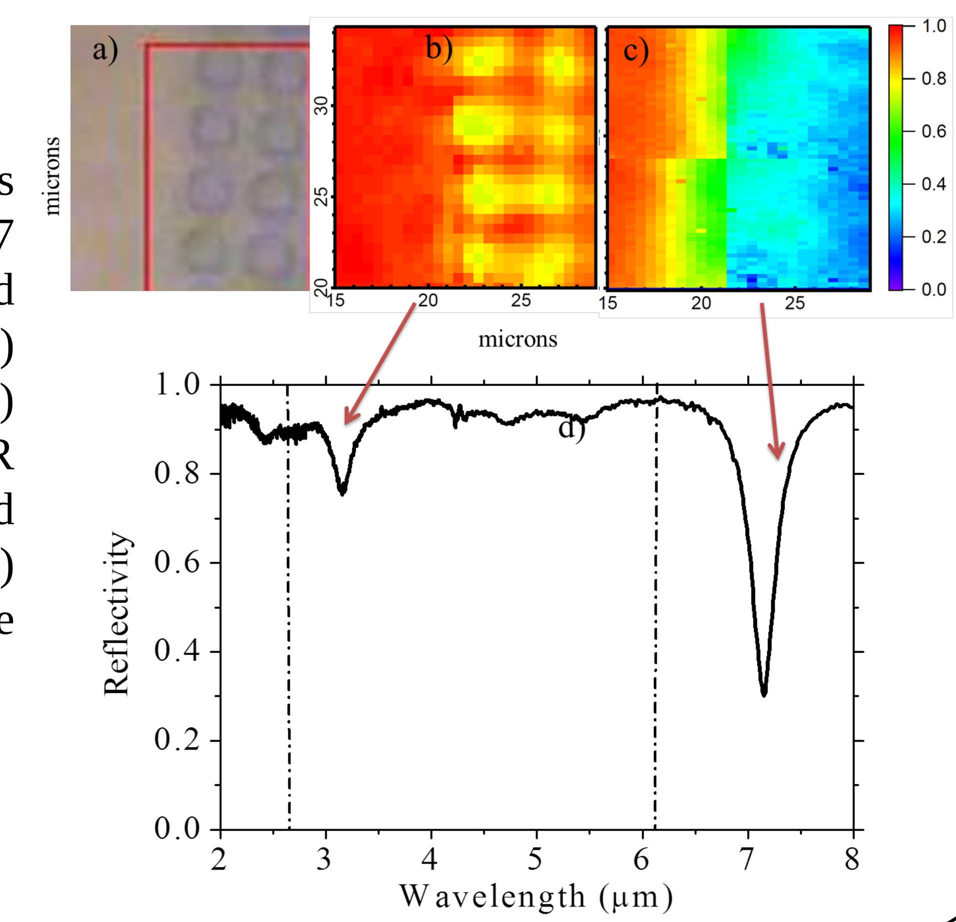


Image of a periodic arrays of the absorber with l=2.7 microns, t=0.1 microns and period, p=4 microns in a) optical microscope, b-c) synchrotron FTIR microscope for 1st order and 0th order respectively d) Reflectivity spectra of the periodic arrays



Summary

We experimentally demonstrated MIM-waveguide theory of metamaterial absorbers in the THz and mid-IR regions. Most of the experimental results are appropriately explained by the theory we developed. We show that there is no need of periodic structures to obtain such absorption. We also show that there is negligible effect from interaction between squares on the resonance wavelength. However, for periodic arrays the absorption obtained is 50% higher than for a 1-cell-metamaterial absorber.