# Tunable Fully Absorbing Metasurfaces for Efficient THz Detection

Lucy L. Hale[1], Polina P. Vabischevich[2,3], Tom Siday[1], Charles Thomas Harris[2,3], John L. Reno[2,3], Igal Brener[2,3], and Oleg Mitrofanov[1,2,3]

[1]Electronic and Electrical Engineering, University College London, London, WC1E 7JE United Kingdom
[2] Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, New Mexico 87123, USA
[3] Sandia National Laboratories, Albuquerque New Mexico 87185, USA

***Abstract*—Terahertz photoconductive antennas with a nanostructured active region have been actively investigated recently with a goal to achieve high efficiency THz detectors and emitters. Here we provide a novel design of perfectly-absorbing photoconductive region without plasmonic elements using a metasurface, and provide a systematic method by which the metasurface can be designed to work optimally for varying optical gate frequencies across the GaAs band-gap. This paves the way to using metasurface devices for THz detection and other applications in a wide range of laser systems operating at different wavelengths or with different photoconductive materials.**

## I.INTRODUCTION

WHILST being a robust, reliable tool for terahertz spectroscopy and imaging, THz antenna detectors and emitters are often limited in efficiency, sensitivity and signal-to-noise ratio. In recent years, novel nanostructuring techniques have been explored to enhance the efficiency of photoconductive antennas, both for detection and emission of THz radiation[1]. Some of the most successful approaches focused on enhancing absorption in the photoconductive layer using plasmonic structures and thereby improving detector performance by increasing optical photon-to-charge carrier conversion efficiency. More recently, all-dielectric photoconductive metasurfaces have been used as the photoconductive region, modifying both the optical and electrical properties of the photoconductive antenna[2]. We have previously shown that by using dielectric metasurfaces we can achieve full optical absorption within the photoconductive region, without the use of added nanostructures such as plasmonic features or back reflectors, which would otherwise increase ohmic losses and add to the fabrication complexity of the device. Here, we provide a detailed description of design principles that allow us to produce a highly-efficient photoconductive metasurface for THz detectors.

In order to obtain full absorption, the photoconductive region can be designed to support two degenerate Mie modes of opposing symmetry. Each of these modes needs to be critically-coupled to the incident field, which involves balancing the absorptive and radiative losses of the mode. Satisfying these two requirements simultaneously is particularly difficult in particularly dispersive regions of the spectrum, such as across the GaAs band-gap, as when modes are tuned in wavelength, this necessarily leads to a breakdown of the critical coupling condition. As a result, the process of adapting fully absorbing metasurfaces for a particular frequency is highly non-trivial. Traditionally, designing metasurfaces involves a large number of simulations, using trial and error to determine the correct device parameters. This can be both time and computationally-intensive, especially if the number of device parameters is large.

We have developed a step-by-step prescriptive approach to designing perfectly absorbing metasurfaces at theoretically any wavelength, even when the intrinsic material losses are exceptionally low. We make use of key design parameters to firstly adjust the modal wavelengths degenerately, and secondly the radiative losses of the modes. Using this method, we design and fabricate metasurfaces that achieve high absorption both at wavelengths where material absorption is high (sufficiently below bandgap) and when material absorption is almost zero (at the bandgap edge).

This technique allows the use of these metasurfaces for terahertz detection in a wide range of systems with varying optical pump wavelength.

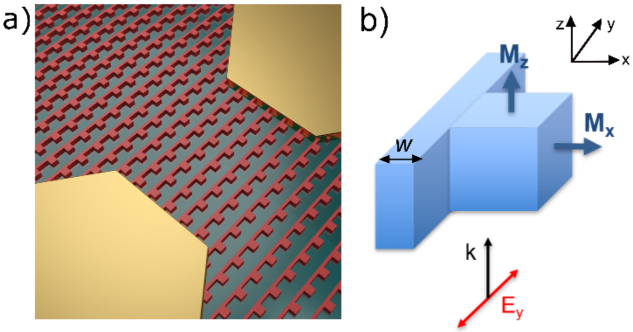

**Fig. 1** a) Picture of all-dielectric metasurface with gold antenna electrodes deposited for THz detection. b) Schematic diagram of the unit cell showing the orientation of magnetic dipoles, $M_x$ and $M_z$.

## II.RESULTS

The design of the metasurface is shown in Figure 1 - the unit cell consists of a dielectric block with a bar attached. The metasurface is made out of low-temperature GaAs (LT-GaAs), in order to take advantage of its beneficial properties for THz detection. By exciting the structure with linearly polarized light, both the in-plane magnetic dipole ($M_x$) and out-of-plane magnetic dipole ($M_z$) are excited (Fig. 1(b)). The bar, as well as providing the asymmetry required to allow excitation of the $M_z$ dipole, also connects neighbouring cells and provide a conducting channel for photoexcited carriers.

Starting from a perfectly absorbing design such as that in ref. [2], in order to satisfy the perfect absorption conditions at a different wavelength the modes need to be shifted degenerately and the critical coupling condition must be satisfied at this new wavelength. Scaling the metasurface in all dimensions may allow degenerate adjustment of the modal wavelengths, but this is often impractical in the fabrication process, and the critical coupling condition will no longer be satisfied. We present a method to tune both the mode wavelengths and critical coupling condition using single parameters that are simple to modify in the fabrication process[3].

Whilst most parameters effect the $M_x$ and $M_z$ mode wavelengths differently, modifying the bar width allows both $M_x$ and $M_z$ modes to be tuned a similar rate over a large range of wavelengths. Therefore, the bar width can be adjusted in order to select the operation wavelength of the metasurface. Figure 2(a) shows the simulated absorption of the modes when the bar width is changed. From ~700 – 900 nm the two modes overlap and appear as one absorption feature, which changes in wavelength with bar width. The tuning, however also leads to a reduction in absorption for dispersive materials, as the critical coupling is no longer satisfied for different intrinsic material absorption. In order to regain high absorption, the radiative losses of the modes can be tuned by varying the periodicity of the unit cell in both x- and y-directions simultaneously (Fig.2(b)). Whilst modifying the periodicities effects the radiative losses of the structure, for our design this has a minimal effect on the modal wavelength. Tuning the periodicity is a particularly important step when fabricating devices out of low-temperature materials, where intrinsic absorption can vary from the material model due to defects[4]. In this case, the periodicity allows the adjustment of radiative losses to match the absorption loss even when it may not be possible to accurately model the material absorption.

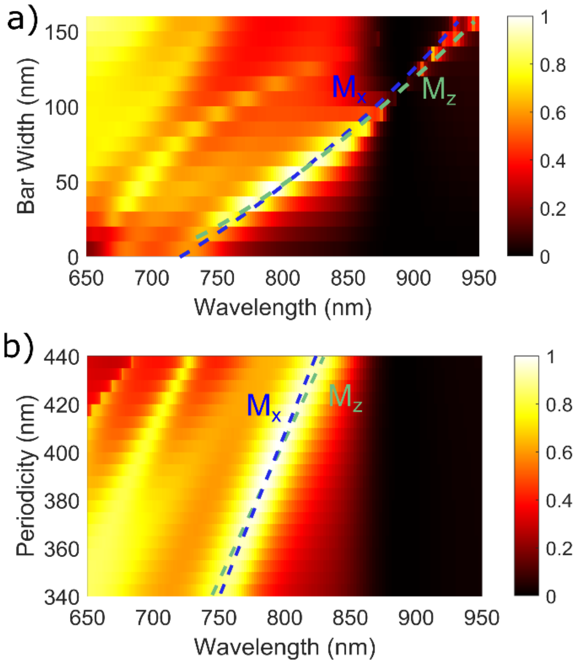

**Fig 2.** Absorption spectra for a) Changing bar width b) Changing periodicity in both x- and y-directions. Mode positions are shown by dotted lines (Mx - blue, Mz - green) [3].

In regions of the spectrum where intrinsic loss is very small, large changes in bar width and periodicity can lead to slight misalignment of the modes, resulting in less-than-full absorption. When this is the case, optimization of the central block size in x- and y- directions can be carried out to regain full absorption.

This technique was used to design two perfectly absorbing metasurfaces at different wavelengths in the range of typical femtosecond pulsed lasers used for terahertz time-domain spectroscopy. Their simulated optical properties are shown in Figures 3(a) and 3(b). One achieves perfect absorption at 790 nm where intrinsic GaAs absorption is high, and the other at the bandgap edge (860 nm), where intrinsic absorption is near-zero. The metasurfaces were fabricated and their measured optical properties are seen in Figures 3(c) and (d). Both structures show very large absorption enhancement in comparison to an unpatterened LT-GaAs layer of the same thickness (black line), This is particularly notable for the longer wavelength structure, where absorption enhancement is 15-fold, despite the extremely low intrinsic absorption of GaAs at this wavelength. We note that we observe slight splitting of the absorption peak in this case, which is due to misalignment of the modes.

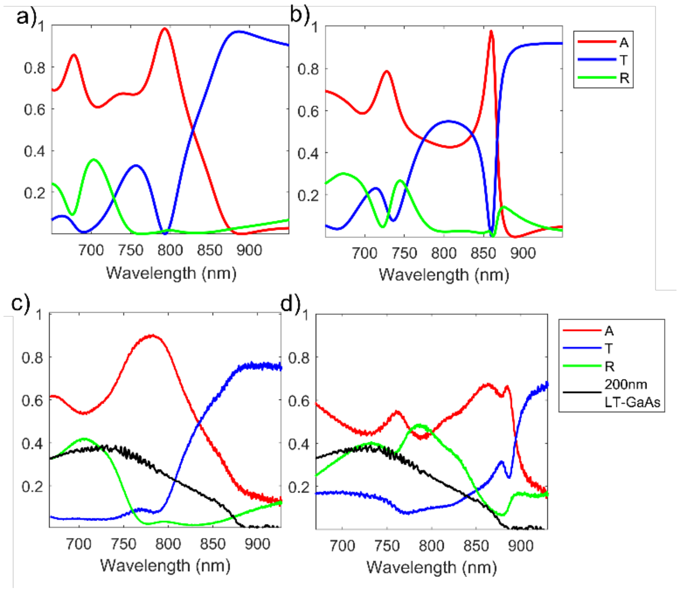

**Fig 3**. a) and b) Optical properties of simulated structures designed at 790 nm (a) and 860 nm (b). c) and d) Optical properties of fabricated structures corresponding to simulated structures in a and b. Absorption (red), transmission (blue), reflectance (green), absorption of 200 nm layer of un-patterned LT-GaAs (black) [3].

## III. SUMMARY

We demonstrate the design and fabrication of perfectly absorbing dielectric metasurfaces which are easily tuned in wavelength by systematically modifying key design parameters. Following this technique, absorption of over a magnitude is achieved in metasurfaces at the bandgap edge. We anticipate that the ability to efficiently tune perfect absorption in photoconductive metasurfaces will allow the use of these devices for detectors and emitters in a wide range of THz imaging and spectroscopy systems.

## ACKNOWLEDGMENTS

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