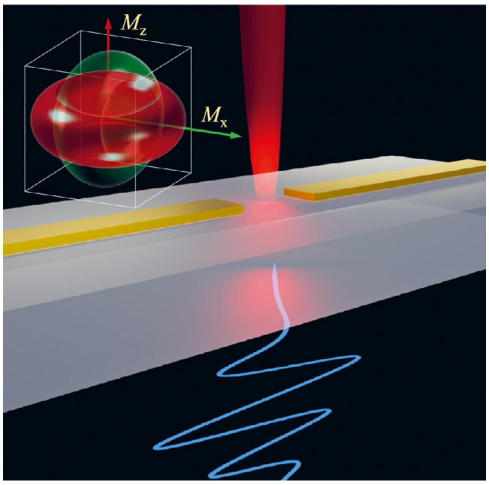
ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES FOR TERAHERTZ APPLICATIONS

Oleg MITROFANOV[1,2] and Igal BRENER[2,3]
[1] University College London, London, WC1E 7JE UK
[2] Center for Integrated Nanotechnologies, Sandia National Labs, Albuquerque, NM 87123, USA
[3] Sandia National Labs, Albuquerque, NM 87185, USA



We review applications of all-dielectric metasurfaces for one of the cornerstone technologies in THz research –ultrafast photoconductive (PC) switches – which are widely used as sources and detectors of broadband THz pulse. Nanostructuring the PC switch channel as a perfectly-absorbing and optically thin PC metasurface allows us to engineer the optical as well as the electronic properties of the channel and improve the efficiency of THz detectors. This approach also opens new routes for employing novel PC materials and enabling new device architectures including THz detector arrays.

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Collections of dielectric subwavelength-size particles can lead to new macroscopic electromagnetic behaviour. Although this fact has been known for many decades, only recently two-dimensional arrays of such objects (*all-dielectric metasurfaces*) have started to emerge as a new paradigm for flat optical components, sensors, modulators and switches [1,2]. The incredible potential of metasurfaces comes from the ability to control amplitude, phase and vector orientation of the electromagnetic field through the size, shape and density of the comprising particles [2]. Here, we review recent developments of all-dielectric metasurfaces for terahertz sources and detectors. Integration of such metasurfaces into the active area of ultrafast photoconductive (PC) switches can lead to over an order of magnitude improvement in the performance of THz photodetectors, and may enable the use of new PC materials and development of detector arrays.

During the early days of THz research, ultrafast PC switches, also known as Auston switches [3], dramatically accelerated the development of the field. With the help of ultrafast lasers, the PC switch enabled electrical conductivity switching on a sub-picosecond time scale. Since then, the Auston switch has been serving as an essential technology for THz applications, enabling generation and detection of THz pulses, THz spectroscopy and imaging. Despite this critical role, the ultrafast PC switch remains highly inefficient, and only a handful of PC materials have been found suitable for the switch due to a demanding combination of required material properties [4].

Several studies recently showed that the switch efficiency can be improved by using plasmonic structures [5-11] and, more recently, all-dielectric metasurfaces [12,13]. By employing the effects of enhanced light absorption and light concentration, it has become possible to achieve better ●●●

performance and enable new device architectures. The PC metasurfaces can revolutionize the PC switch technology and lead to more efficient THz radiation detectors and sources.

ULTRAFAST PHOTOCONDUCTIVE SWITCH

We start with the operation principle of the PC switch for detection of THz pulses [3,4]. In the original design (Fig. 1), the PC switch contained a bulk PC region, which can be turned ON optically, and two electrodes, which collect the induced photocurrent. The electrodes also function as an antenna for capturing or emitting THz waves. In the OFF state, the resistance of the PC region is very high and no current flows through the channel; when the switch is illuminated with a near-infrared (NIR) pulse from an ultrafast laser the resistance drops by several orders of magnitude initiating charge transport in the channel. In the presence of a THz wave, the antenna picks up its electric field and induces a voltage bias across the channel. A photocurrent flows in the direction of the THz field until the optical excitation stops. The switch operates as a gated detector of the THz electric field, with NIR light acting as the gate. It allows sampling the electric field of the THz pulse in the time domain, like an ultrafast sampling oscilloscope.

Although the operation principle is simple, it can be implemented only with PC materials, which enable three key physical processes: conversion of a short burst of incident photons into mobile charge carriers; conduction of the photocarriers in response to an external THz field, and fast elimination of the carriers from the channel after the optical excitation ends. These processes dictate three essential requirements for the switch: efficient photo generation of charge carriers, high contrast between the ON and OFF states, and extremely short (sub-picosecond) carrier lifetime.

Fulfilling all three requirements is a challenge. Due to the limited drift velocity in the PC materials, the photoexcited carriers are able to travel only a short distance (<100 nm) before they must recombine and switch the channel OFF. As a result, only the photocarriers generated within a distance of 50–100 nm from the electrodes contribute to the photocurrent. However, the probability for an incident photon to be absorbed within that distance is very small (*e.g.* the top 100 nm thick layer of GaAs absorbs about 7% of incident photons at 800 nm). The sub-picosecond carrier lifetime therefore inherently limits the conversion efficiency.

Enhancing optical absorption while reducing the size of the PC channel therefore is one of the main strategies. One solution that has been explored extensively so far has been to concentrate the optical fields near the electrodes using metallic structures supporting plasmonic resonances, *e.g.* electrodes with nanoscale interdigitated fingers [5,6] and field concentrating elements [7,8]. Several examples are illustrated in Figure 2. Excitation of plasmonic resonances leads to generation of the photocarriers mainly ●●●

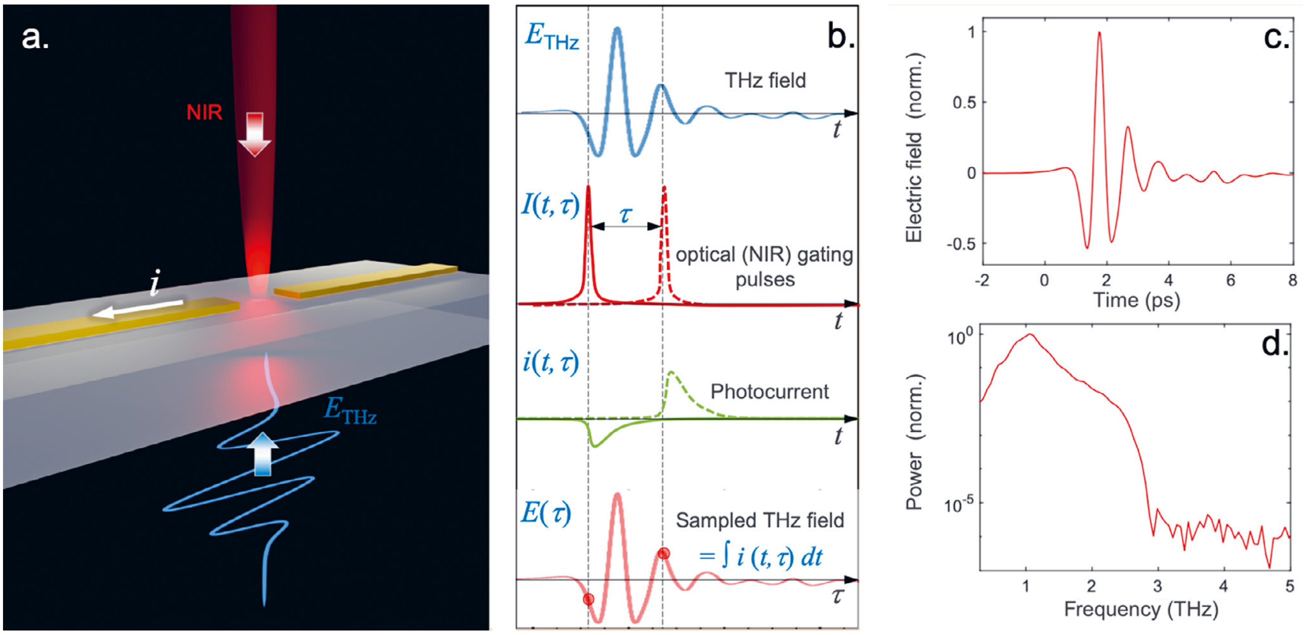


Figure 1.
Operation principle of the photoconductive (PC) switch for THz detection. a. PC switch illustration. b. Process of PC sampling: the switch is illuminated by a THz pulse (top) and a NIR gating pulse (upper middle) with a variable delay between the two pulses. The NIR pulse generates charge carriers and the THz field drives them toward electrodes. A THz pulse waveform is reconstructed in time domain using the time-averaged photocurrent $i(t,\tau)$ recorded for different time delays τ (bottom). c. Electric field waveform and d. the Fourier power spectrum of a THz pulse detected using a switch with a PC metasurface channel *(from Ref. 13).*

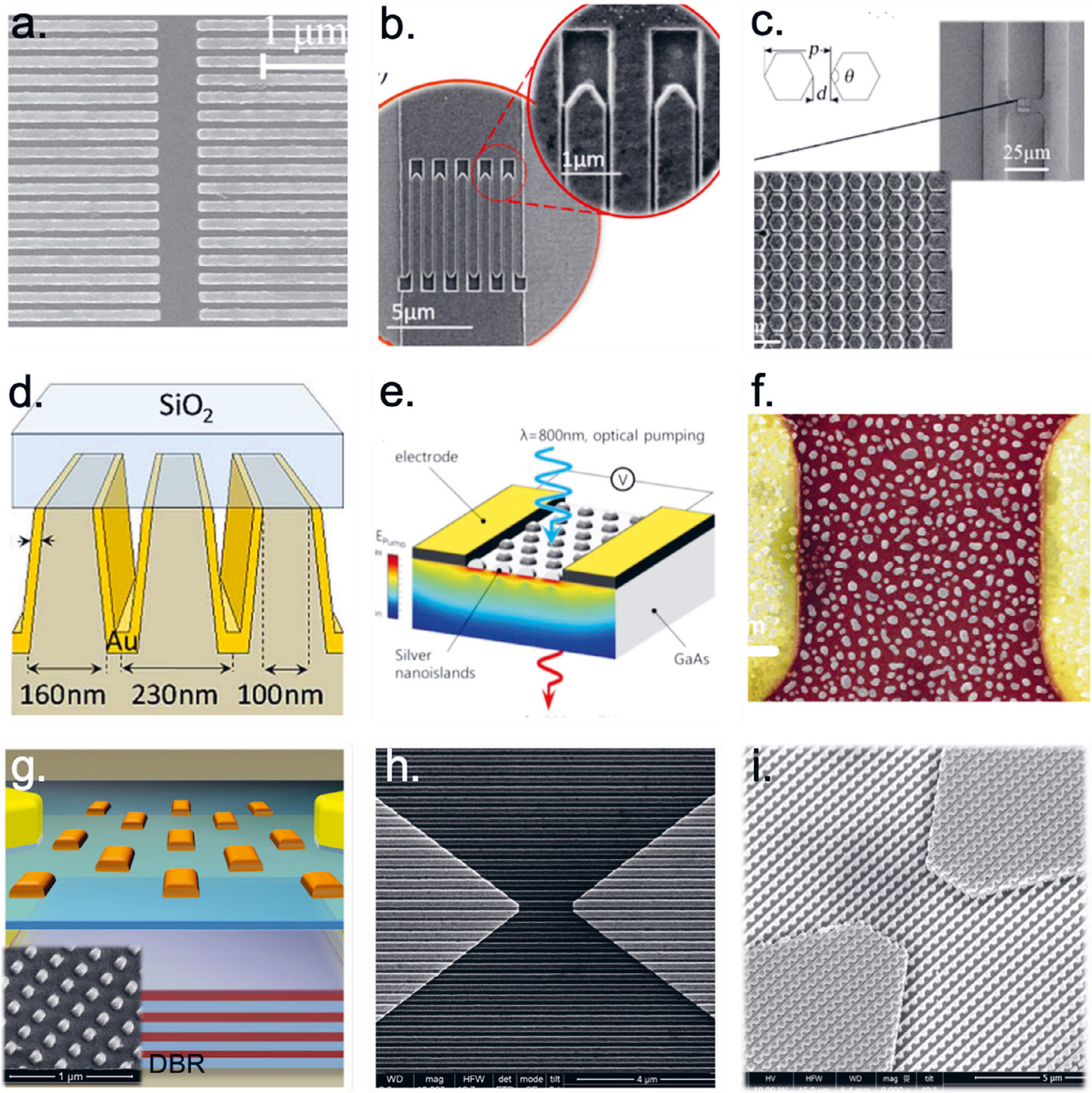


Figure 2.
Examples of nanostructured PC regions in THz switches. a. Plasmonic nanoantenna array [5]; b. Interdigitated electrodes with nanoscale gaps [6]; c. Plasmonic field concentrators [7]; d. Three-dimensional plasmonic electrodes [8]; e, Periodic arrays [9] and f. Random distribution of plasmonic nanoparticles [10]; and g. Hybrid PC optical cavity [11]. All-dielectric PC metasurfaces: h. Nanobeams with a DBR underneath [12] and i. Perfectly-absorbing network of cubic resonators [13].

within a short distance from the electrodes (~50 nm). Unfortunately, these types of electrodes tend to reduce the OFF-state resistance.

Another plasmonic strategy is to engineer the channel as an optically thin metasurface where the majority of incident photons are absorbed [9-10]. We developed such a metasurface earlier using periodic arrays of nanoantennae over the channel with a distributed Bragg reflector (DBR) below it [11]. The antennae and the DBR form an optical cavity with an ultrathin PC channel, which can be as thin as 50 nm. The antennae are electrically isolated, and the channel OFF-state resistance remains high.

Despite enhancing the overall absorption in the channel, plasmonic elements have another major limitation: they tend to introduce ohmic losses which limit the efficiency and make

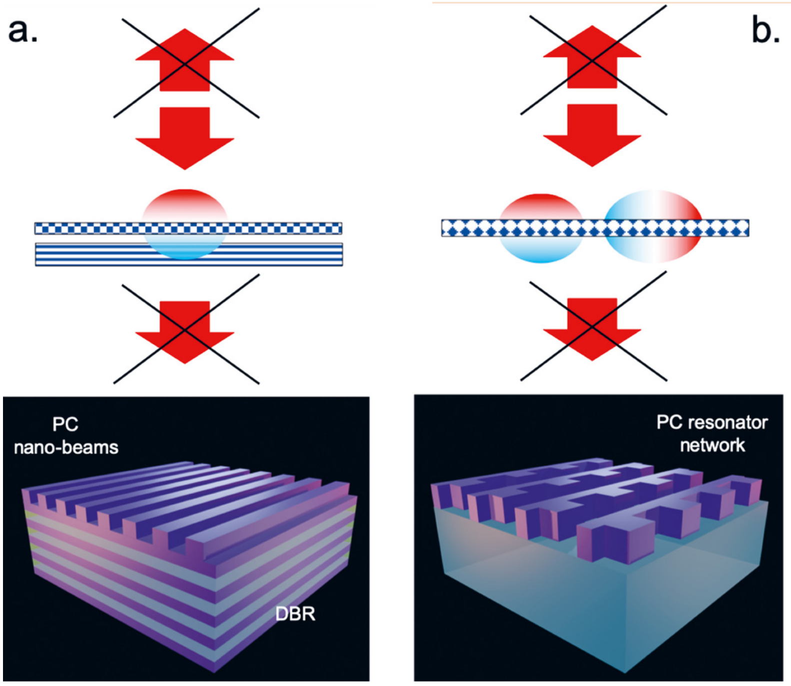
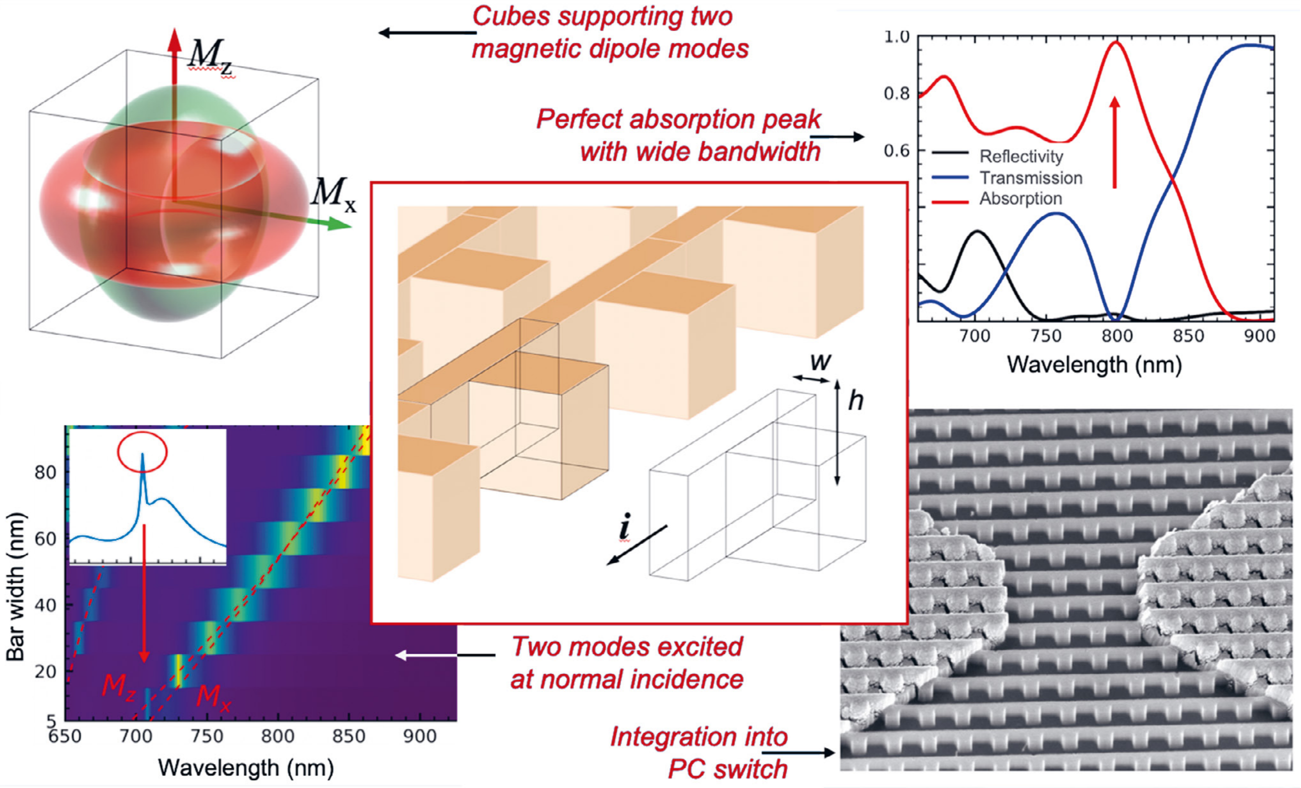


Figure 3.
Perfect absorption schemes in all-dielectric PC metasurfaces. a. Resonant nanobeams with a distributed reflector; and b. Network of cubic resonators with broken symmetry.

Figure 4.
Perfectly-absorbing network of PC resonators. The metasurface consists of an array of cubes connected by side bars into a network (center). Each cube supports MD modes (top left) and the bar allows excitation of the dark mode M_z. Perfect absorption occurs if the modes are degenerate (top right); the modes are tuned by adjusting the cube or the bar geometry (bottom left, from Ref. 13). The metasurface serves as the PC channel (bottom right).



Cubes supporting two magnetic dipole modes

Perfect absorption peak with wide bandwidth

Two modes excited at normal incidence

Integration into PC switch

The combination of a higher photocurrent and a higher dark resistance is ideal for a THz detector, as it leads to the highest signal to noise ratio (SNR) at a relatively small level of required incident gating power.

devices more susceptible to thermal damage. All-dielectric metasurfaces provide an alternative route to enhanced photon absorption. In the next section we present two schemes, where the PC channel is structured as a *perfectly absorbing all-dielectric metasurface*.

PERFECT ABSORPTION IN ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES

A. NANOSTRUCTURE SUPPORTING AN OPTICAL RESONANCE WITH A REFLECTOR UNDERNEATH THE SURFACE

Enhanced absorption in the first approach is achieved through manipulation of the amplitude and phase of reflected waves for the nanostructured top surface and the distributed Bragg reflector (DBR) below it. For the top-surface structure, we designed the PC channel as an array of resonant nanoscale beams (*nanobeams*), similar to a high-contrast grating. For the DBR, we introduced a standard quarter-wave stack of dielectric layers [Fig. 3(a)]. This structure supports a resonance with spatial field distribution similar to a magnetic dipole mode [12].

An intuitive understanding of this scheme can be gained by considering reflection from the nanostructured surface and the DBR. The nanobeams provide a narrow-band reflection peak corresponding to the resonance, whereas the DBR provides uniform reflectivity within a wider stopband. By controlling the size of the nanobeams, their density and position with respect to the reflector, we minimize reflection through destructive interference of the wave reflected by the DBR and by the nanobeams. This condition leads also to a rise in absorption [12].

B. NANOSTRUCTURE SUPPORTING TWO DEGENERATE AND CRITICALLY COUPLED MIE RESONANCES OF ODD AND EVEN SYMMETRY

In the second approach we employed the perfect absorption scheme that relies on excitation of two degenerate Mie modes of opposite symmetry - odd and even - with respect to the metasurface plane [Fig. 3(b), 13]. Such a structure exhibits perfect absorption at the Mie resonance wavelength if both modes are critically coupled [14-15]. To realize this concept, we designed a cubic resonator supporting magnetic dipole (MD) modes. We chose the MD modes due to the strongest confinement of the field in the dielectric. The cubic symmetry supports three degenerate MD modes: two of the modes have their dipole moments, M_x and M_y, in the *xy*-plane; the corresponding in-plane electric field distributions are odd with respect to the metasurface plane. The dipole moment of the third mode M_z is orthogonal to the plane, and the corresponding in plane electric field distribution is even with respect to the plane. Perfect absorption can occur when two mode pairs, M_x with M_z, or M_y with M_z, are excited simultaneously. M_z is required in both cases, however it possesses rotational symmetry in the surface plane and therefore cannot be excited by a linearly polarized plane wave at normal incidence. To enable excitation of this dark mode we break the cubic symmetry of the resonators by introducing a bar aligned along one side of the cubes (Fig. 4). With direct excitation of M_z under normal incidence, the condition of perfect absorption is reached by adjusting the size of the bar and the array periodicity [13].

PERFORMANCE OF ALL-DIELECTRIC PHOTOCONDUCTIVE METASURFACES

Structuring the PC region as a perfectly-absorbing metasurface enables efficient photoexcitation of the channel. Our experimental studies of both designs implemented in low temperature (LT) grown GaAs showed strong absorption enhancement at 800 nm. Furthermore, the wavelength range where the absorption is enhanced is sufficiently wide for short pulse excitation (Fig. 4). For both designs, we observed that the photocurrent response increased by an order of magnitude when compared with unstructured PC channels of similar dimensions [12,13].

The switching contrast also increased due to the small physical cross-section of the channels. In the resonator network case, the cross-section of each side bar was only 0.01 μm^2 (Fig. 4). As a result, the dark resistance of the resonator network was as high as 50 GΩ, about 1-2 orders of magnitude higher in comparison to detectors based on unstructured LT GaAs layers [13]. The higher resistance leads to a higher ON/OFF switching contrast and better performance of THz detectors.

The combination of a higher photocurrent and a higher dark resistance is ideal for a THz detector, as it leads to the highest signal to noise ratio (SNR) at a relatively small level of required incident gating power. For the PC metasurface designed as the resonator network, we observed the best SNR for a gating power of only 100 µW [13], which is more than one order of magnitude lower than the optimal operation power required for conventional THz detectors.

CONCLUSIONS

Photoconductive all-dielectric metasurfaces provide a promising new approach for developing efficient THz radiation detectors and THz radiation sources. They can enable close to perfect optical absorption of photons in the photoconductive channel and higher ON/OFF switching contrast, and thus lead to operation at significantly lower switching power levels with excellent noise performance. This approach can revolutionize the photoconductive switch technology by opening doors to new photoconductive materials and routes to novel applications which were deemed impractical previously, such as THz detector arrays, whereas the new architecture of the channel opens exciting opportunities for research on photoexcited carrier dynamics and for innovations in metasurface engineering.

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REFERENCES

[1] S. Jahani and Z. Jacob, All-dielectric metamaterials, *Nat. Nanotechnology* **11**, 23 (2016)

[2] I. Brener, S. Liu, I. Staude, J. Valentine and C. Holloway, Dielectric Metamaterials: Fundamentals, Designs, and Applications, Woodhead Publishing (2019)

[3] D.H. Auston and M.C. Nuss, *IEEE J. Quantum Electron.* **24**, 184 (1988).

[4] E. Castro-Camus and M Alfaro, Photoconductive Devices for Terahertz Pulsed Spectroscopy: A Review, *Photonics Res.* **4**, A36 (2016)

[5] N. T. Yardimci and M. Jarrahi, High Sensitivity Terahertz Detection through Large-Area Plasmonic Nano-Antenna Arrays, *Sci. Rep.* **7**, 42667 (2017)

[6] B. Heshmat *et al.*, Nanoplasmonic Terahertz Photoconductive Switch on GaAs, *Nano Lett.* **12**, 6255–6259 (2012)

[7] F. Fesharaki *et al.*, Plasmonic Antireflection Coating for Photoconductive Terahertz Generation, *ACS Photonics* **4**, 1350-1354 (2017)

[8] S.-H. Yang *et al.*, 7.5% Optical-to-Terahertz Conversion Efficiency Offered by Photoconductive Emitters with Three-Dimensional Plasmonic Contact Electrodes, *IEEE Trans. Terahertz Sci. and Technol.* **4**, 575-581 (2014)

[9] S. G. Park *et al.*, *Opt. Express* **20**, 25530–25535 (2012).

[10] S. Lepeshov *et al.*, Boosting Terahertz Photoconductive Antenna Performance with Optimised Plasmonic Nanostructures, *Sci. Rep.* **8**, 6624 (2018)

[11] O. Mitrofanov *et al.*, Photoconductive Terahertz Near-Field Detector with a Hybrid Nanoantenna Array Cavity, *ACS Photonics* **2**, 1763–1768 (2015)

[12] O. Mitrofanov *et al.*, Efficient Photoconductive Terahertz Detector with All-Dielectric Optical Metasurface, *APL Photonics* **3**, 51703–51703 (2018)

[13] T. Siday *et al.*, Terahertz Detection with Perfectly-Absorbing Photoconductive Metasurface, *Nano Lett.* **19**, 2888-2896 (2019)

[14] M.A. Cole *et al.*, Strong Terahertz Absorption in All-Dielectric Huygens' Metasurfaces. *Nanotechnology* **27**, 424003 (2016).

[15] X. Ming *et al.*, Degenerate Critical Coupling in All-Dielectric Metasurface Absorbers, *Opt. Express* **25**, 24658 (2017)