

Smart devices for terahertz wavefront manipulation

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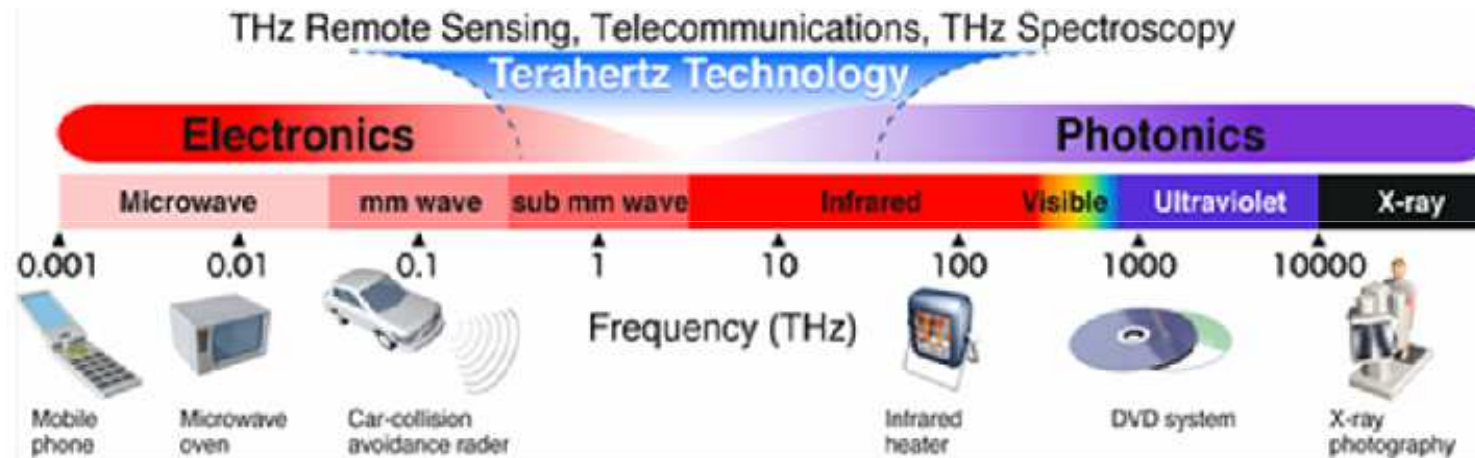
Yan Zhang

2013. 09. 14

Outline

- **Introduction of THz**
- **Metasurface based devices for THz wavefront control**
- **Active control of THz wavefront**
 - Optical control of THz wavefront via metasurface
 - Optical control of THz wavefront via optically generated hologram
- **Conclusions**

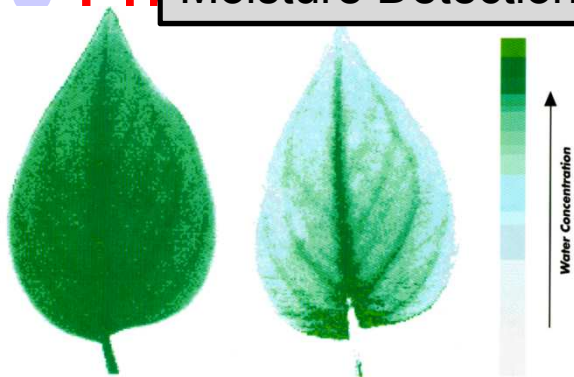
1 THz~1 ps~300 μm ~33 cm^{-1} ~4.1 meV



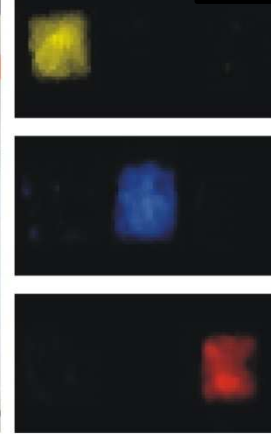
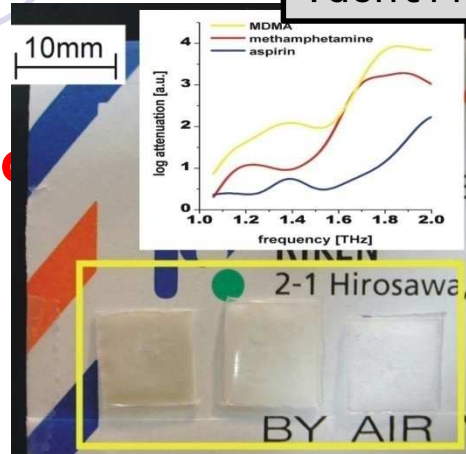
- **Terahertz (THz, 1 THz=10¹² Hz), sandwiched between the microwave and infrared**

Unique nature

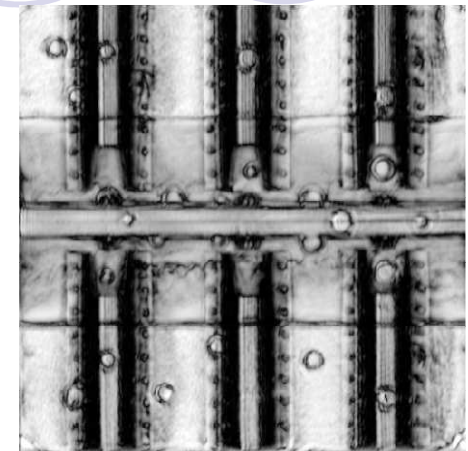
- Coherent detection
- Transparent
- Low photon energy
- Fine Moisture Detection



Identification



Nondestructive Inspection

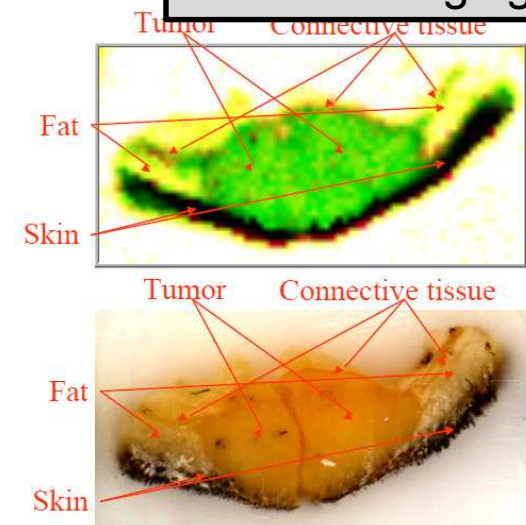


Safety Inspection



Spot the knife? Millimeter waves, close to terahertz, show their ability to see through clothes and paper.

Medical Imaging



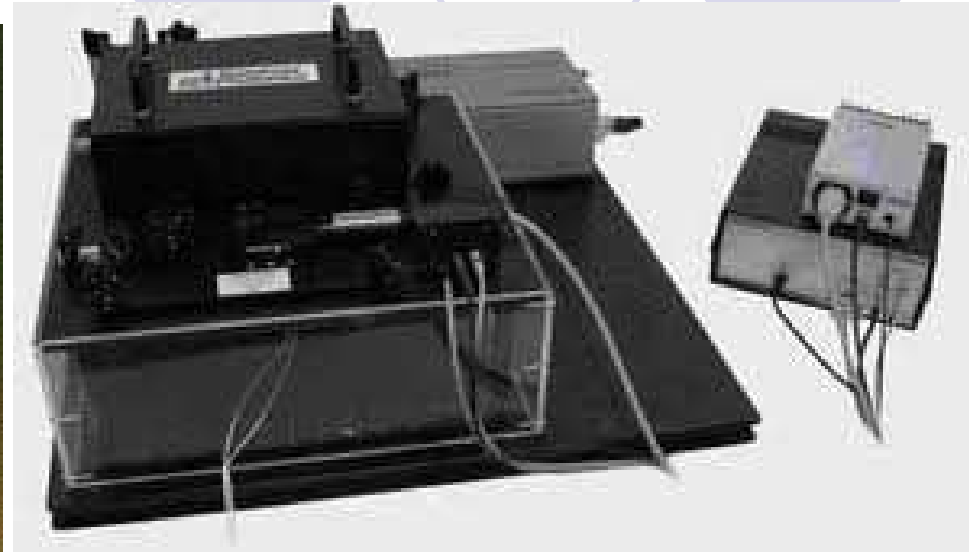
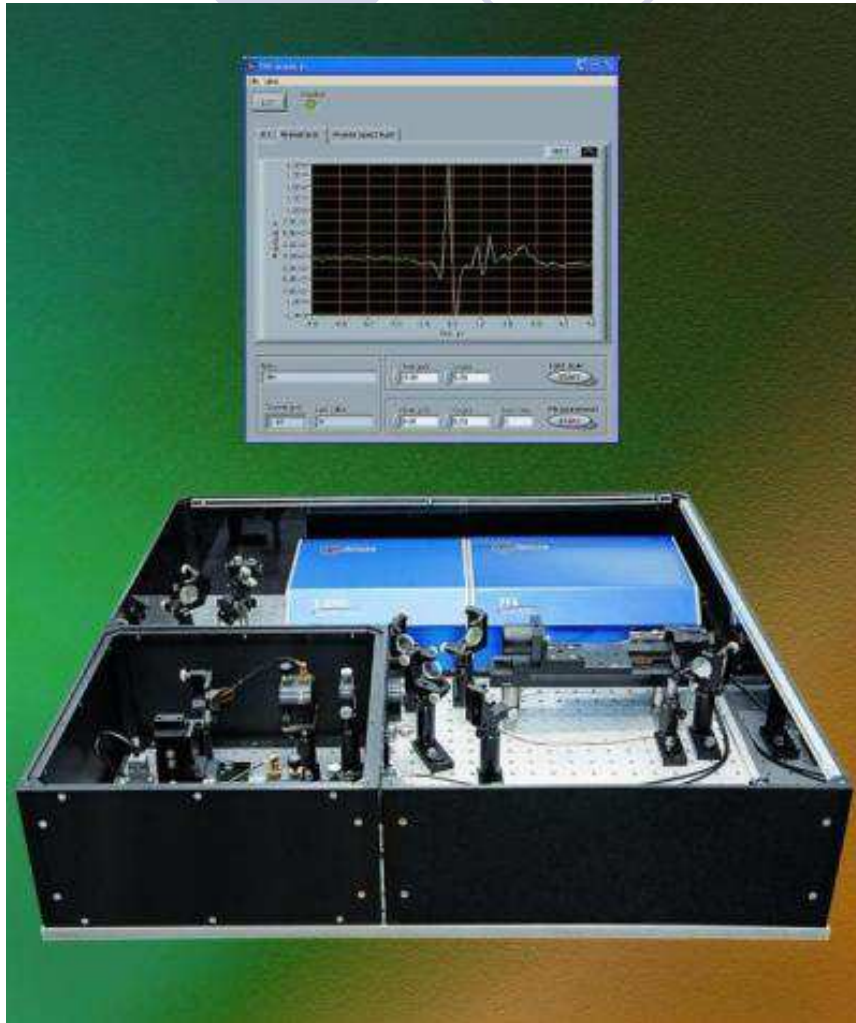
Applications of Terahertz

Defense: homeland security, chemical and biological agents detection, explosives detection, see-through-the-wall, imaging in space using satellites.

Commercial: biomedical, such as skin imaging for cancer detection, forgery, mail inspection, luggage inspection, gas spectroscopy, non-contact and non-destructive method.

Research: physics, plasma fusion diagnostics, electron bunch diagnostics, THz wave microscope, zero resistivity under THz radiation, Left Hand Materials (LHM) at THz range, THz spintronics.

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**THz system is too huge for
real applications.**

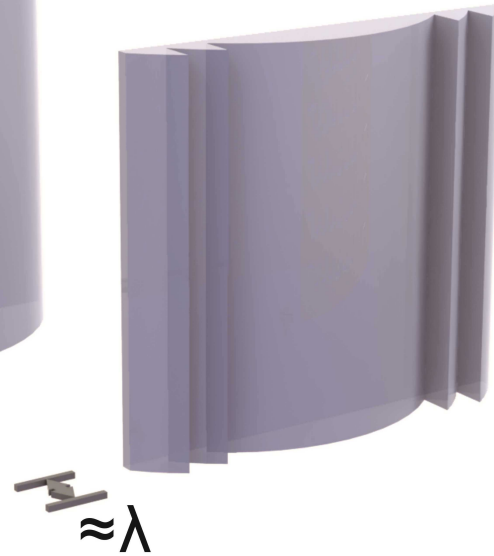
**More flexible method for
wavefront control**

How thick can a lens be?

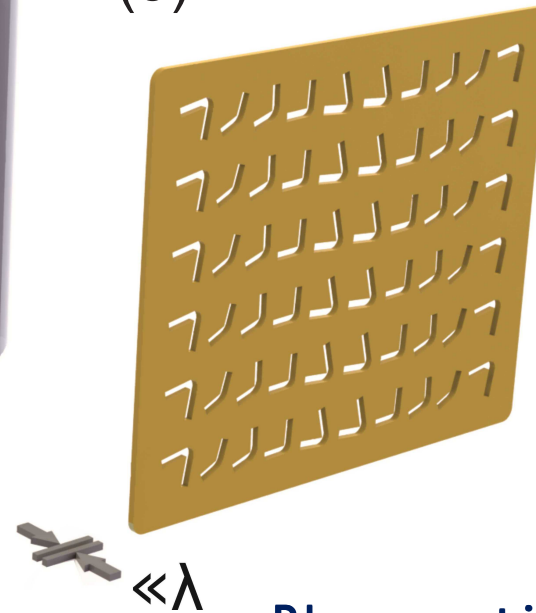
(a)



(b)



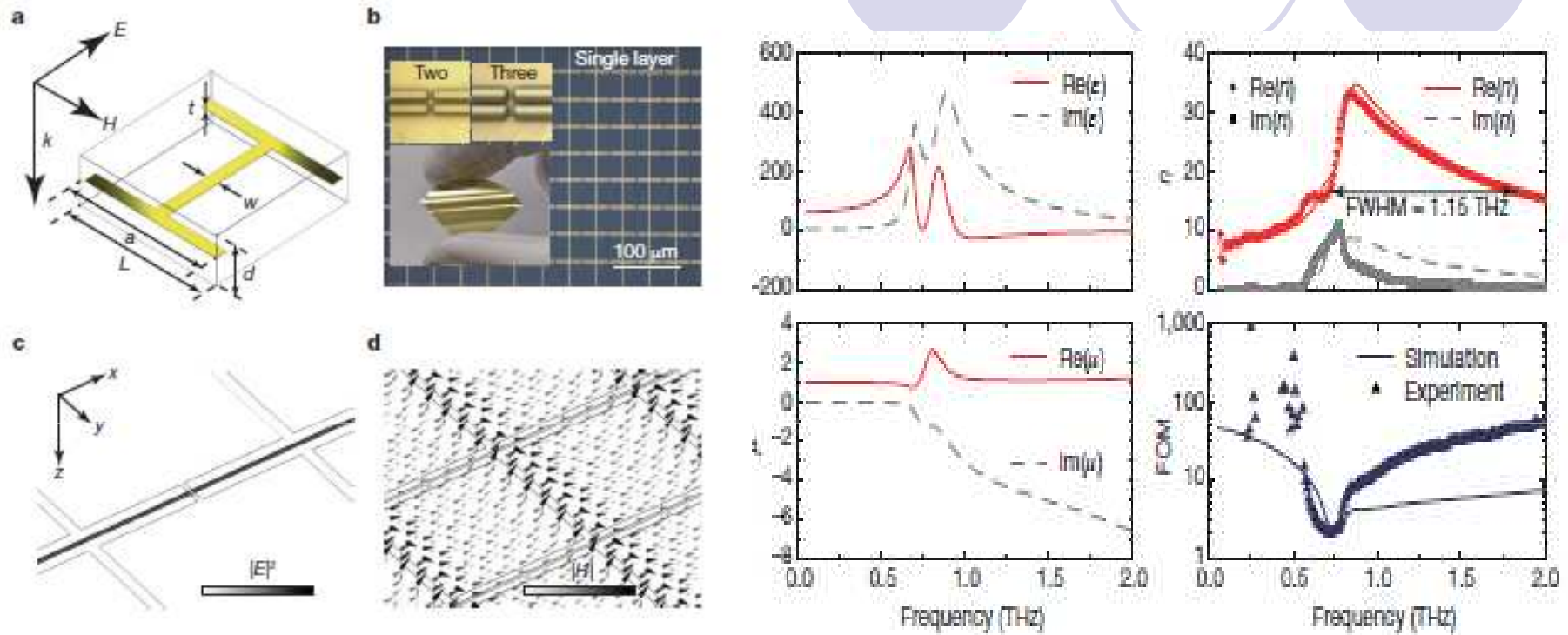
(c)



Traditional optical element

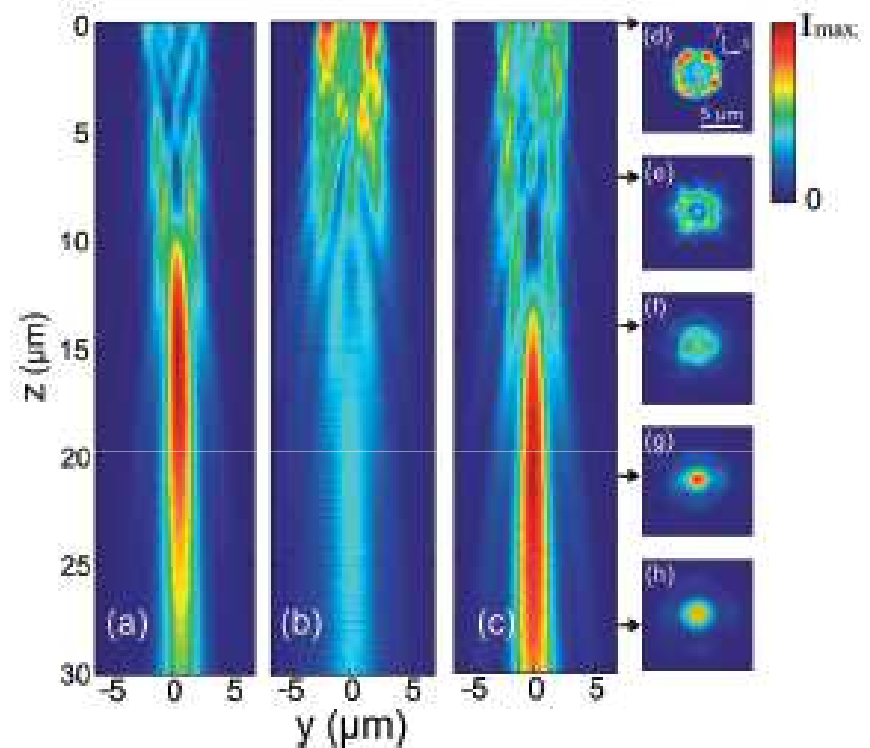
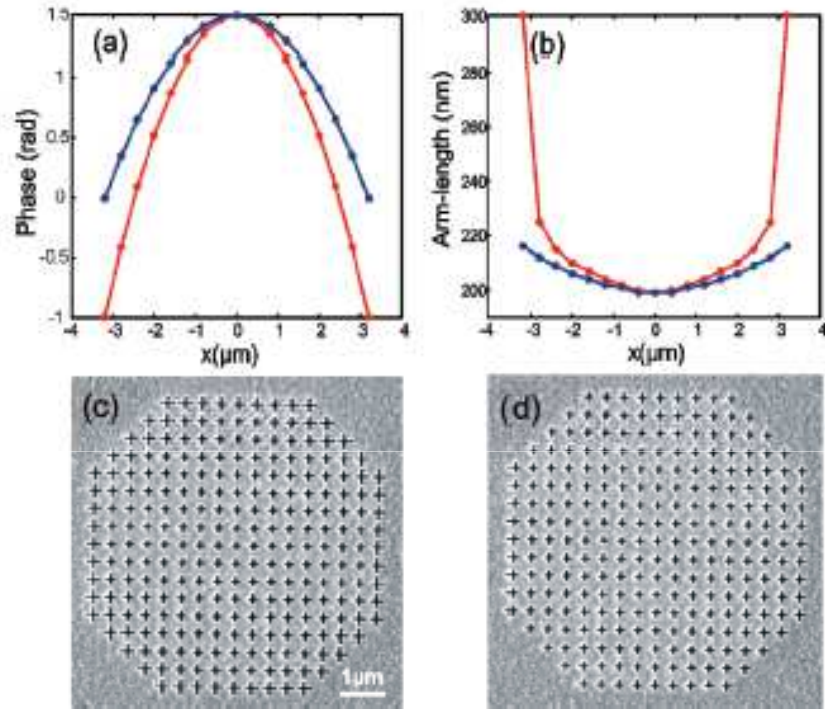
Planar optical element

Diffractive optical element



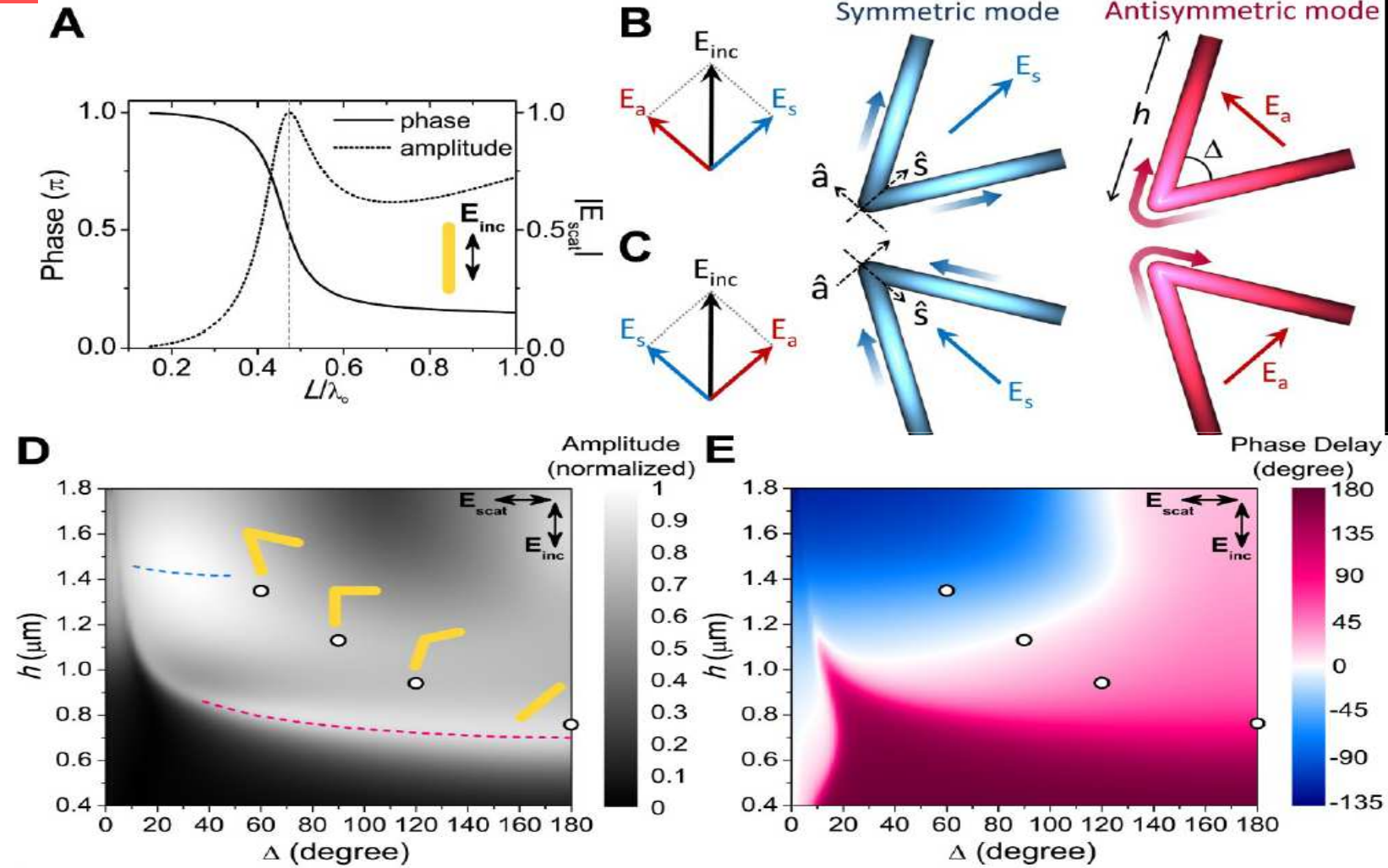
A terahertz metamaterial with unnaturally high refractive index

Nature. 2011, 470, 369—373



Plasmonic Lenses Formed by Two-Dimensional Nanometric Cross-Shaped Aperture Arrays

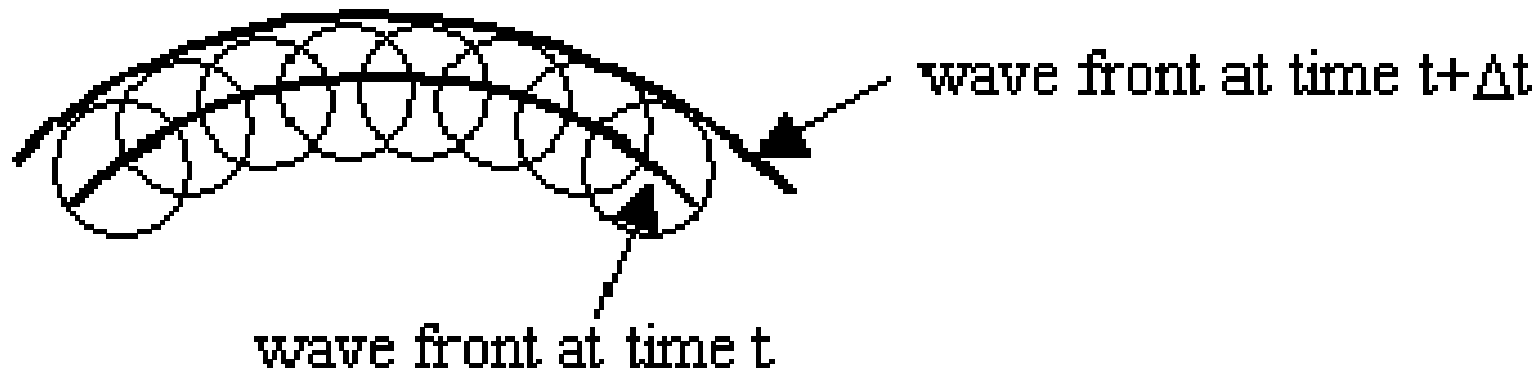
Nano Lett. 2010, 10, 1936–1940

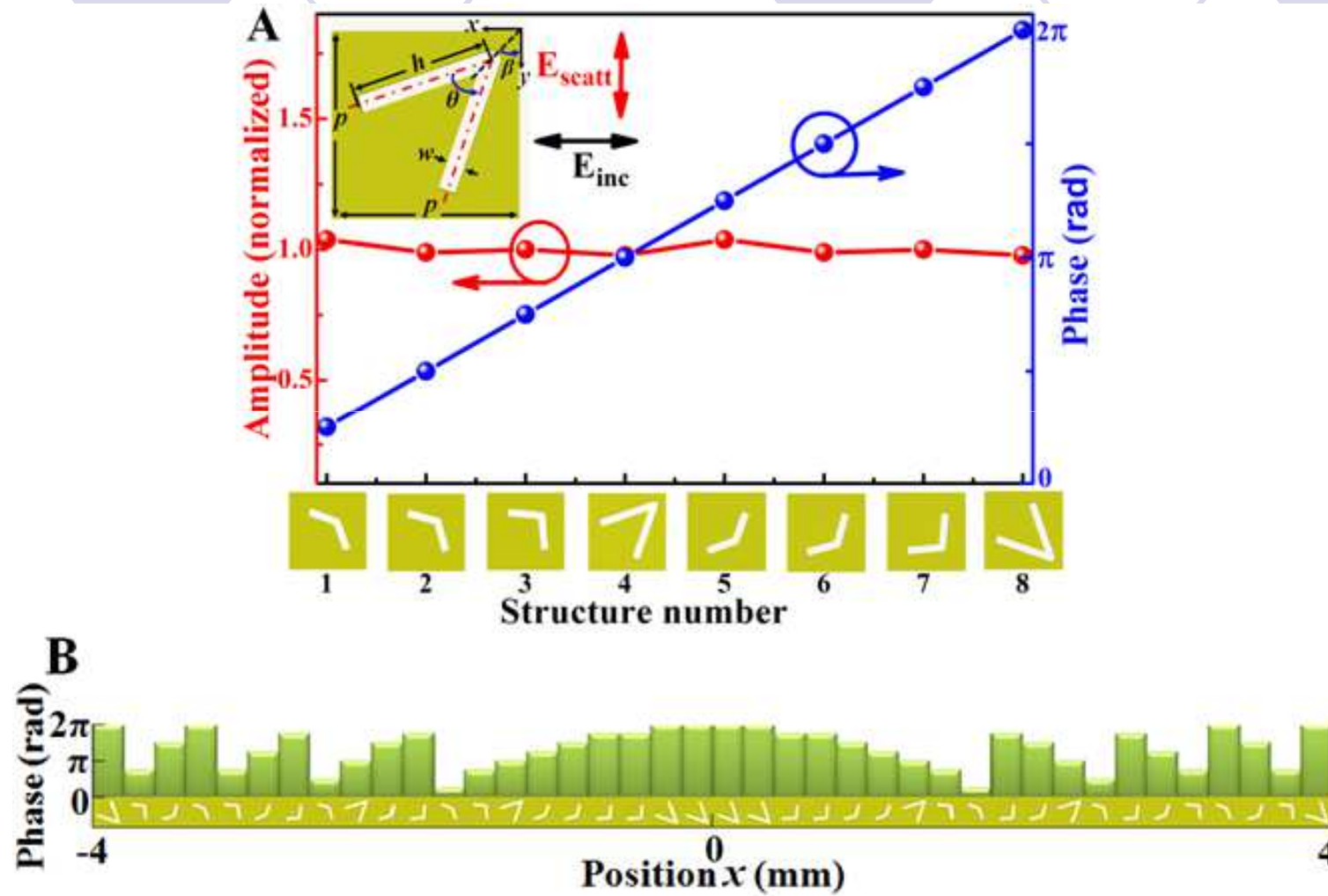


Phase modulation based on antenna resonance

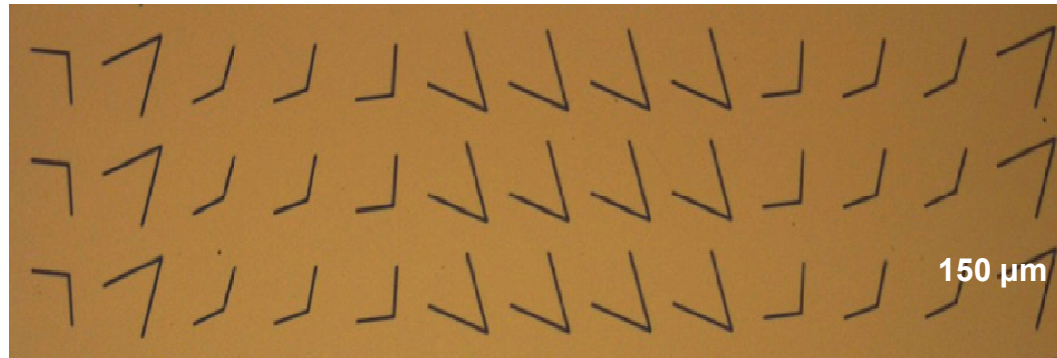
Huygens' Principle

The wavefront of a propagating wave of light at any instant conforms to the envelope of spherical wavelets emanating from every point on the wavefront at the prior instant.





Part of cylindrical lens



Focal length:
4mm@400μm

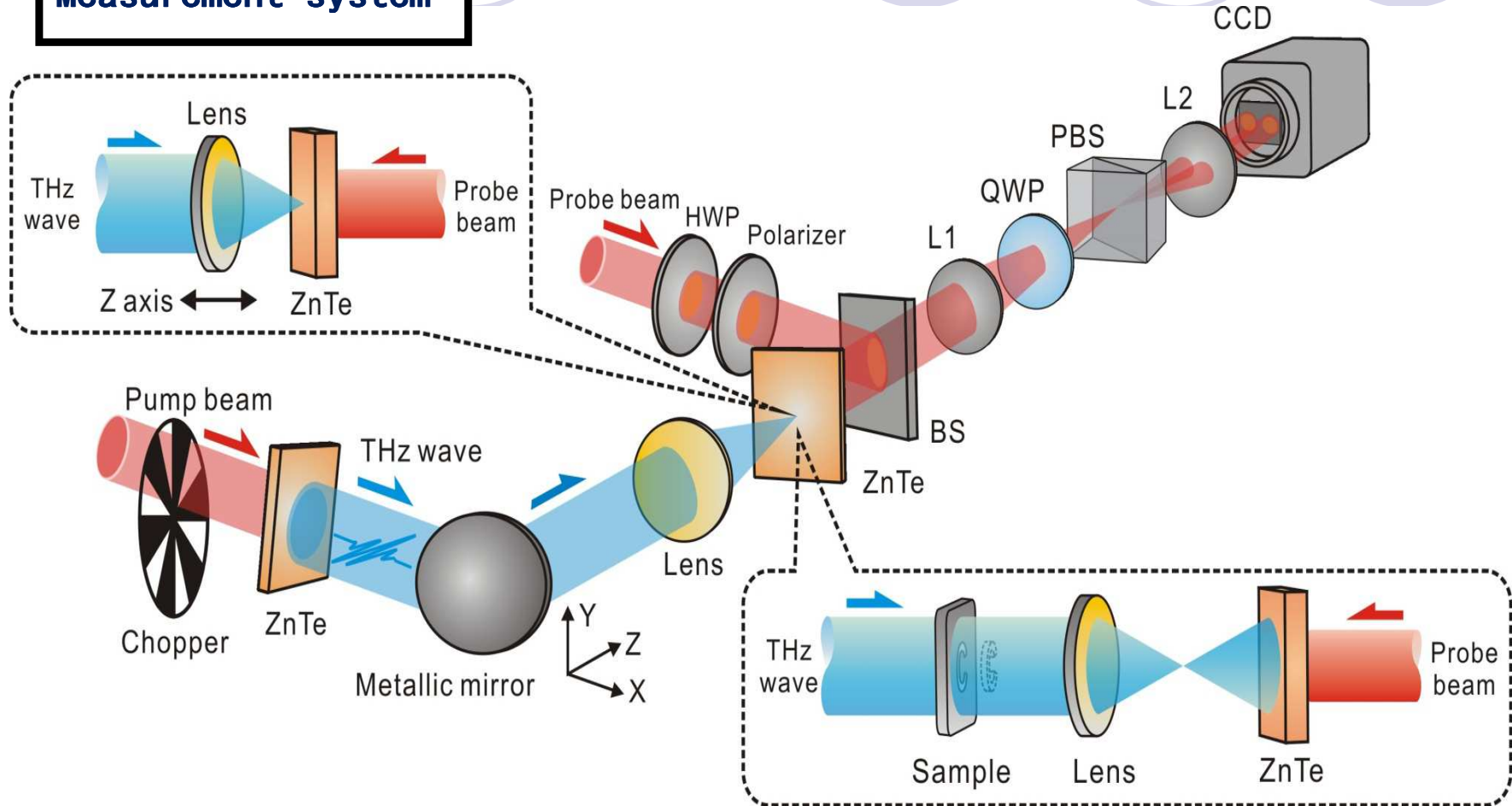
Part of spherical lens

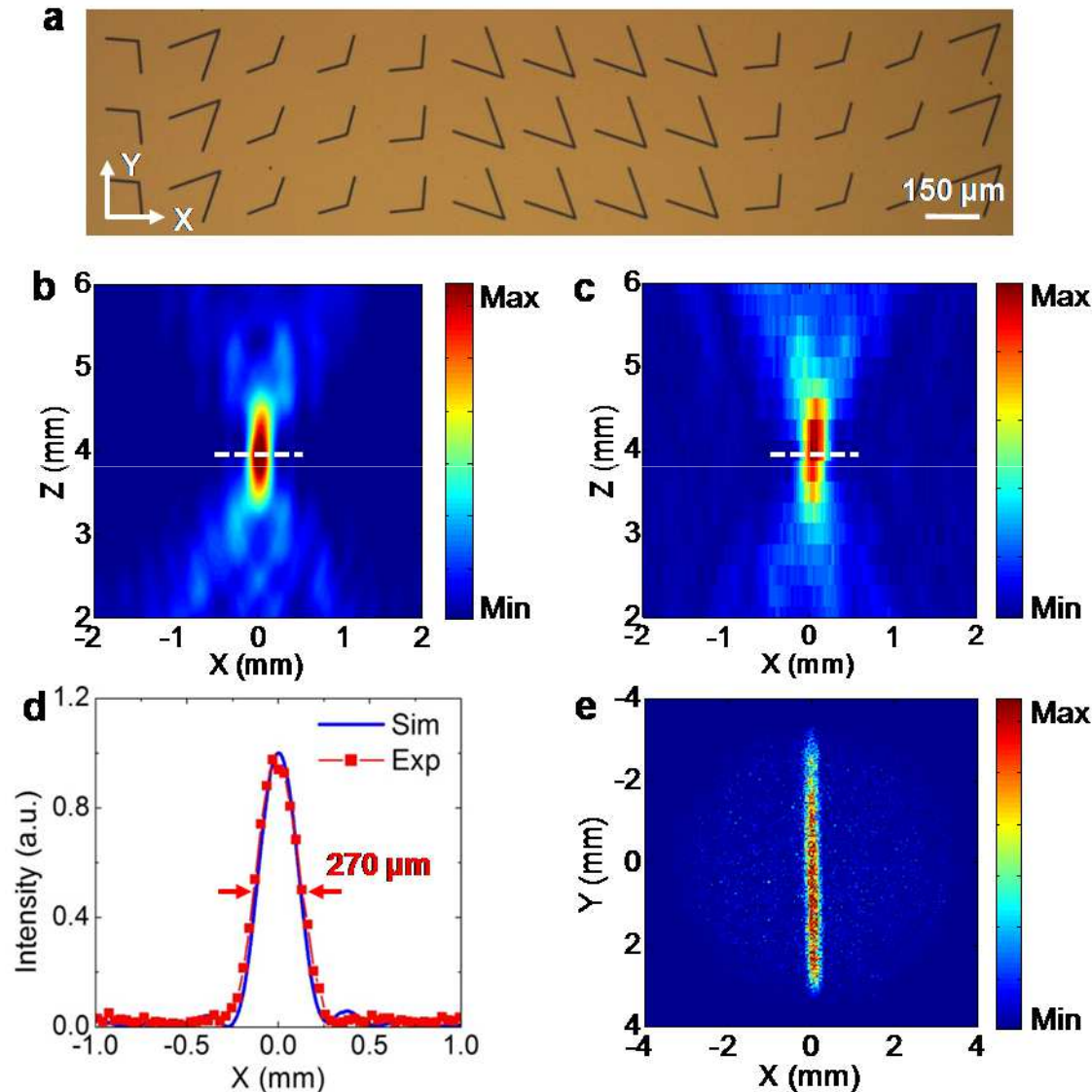
Focal length:
4mm@400μm



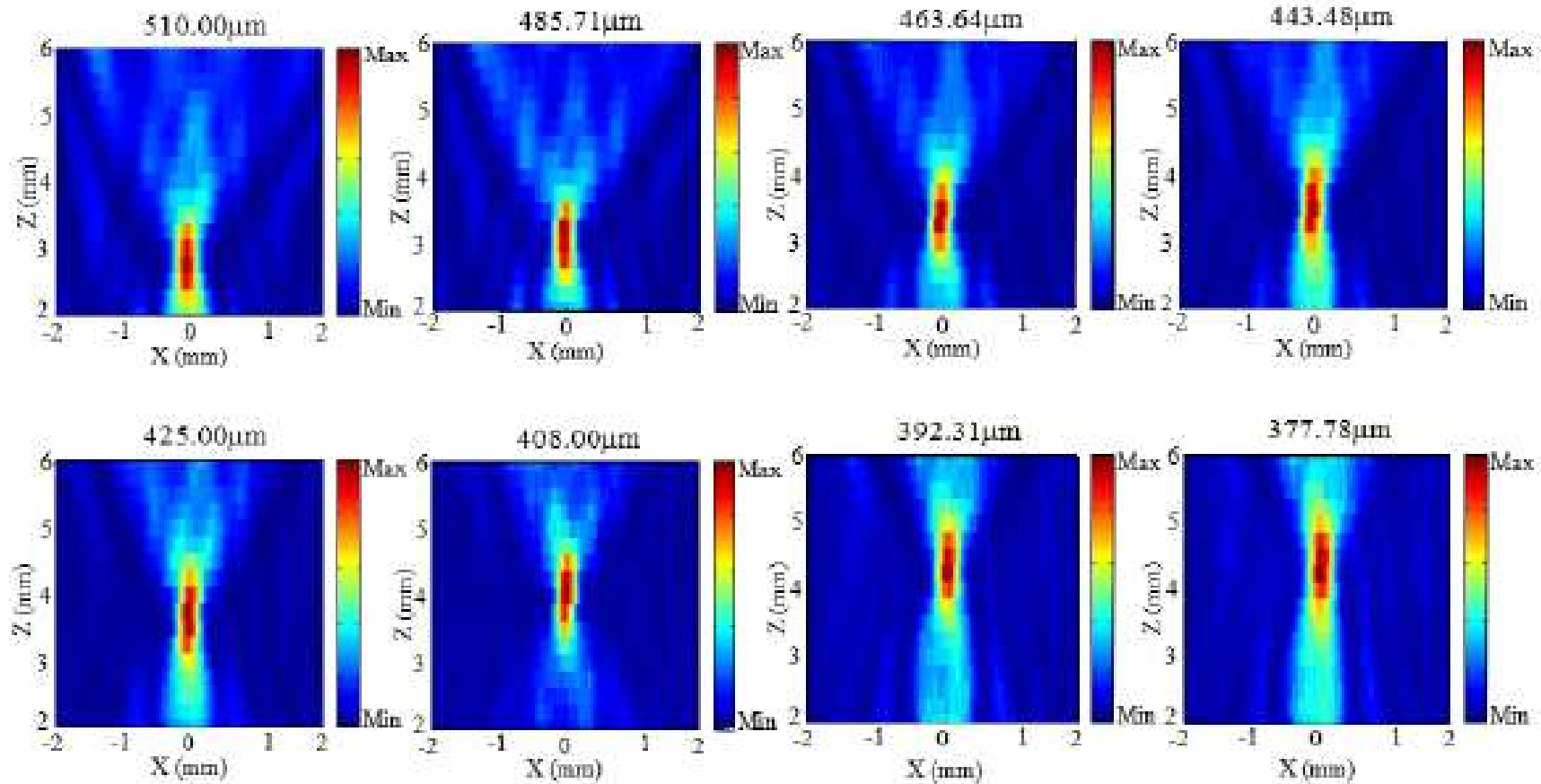
100nm gold on 500um silicon

Measurement system





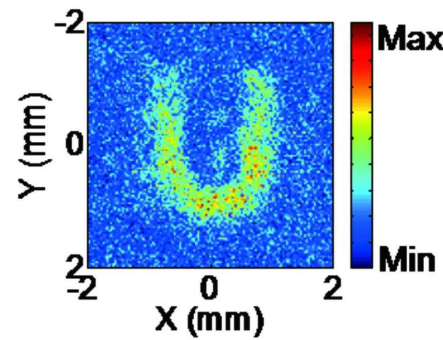
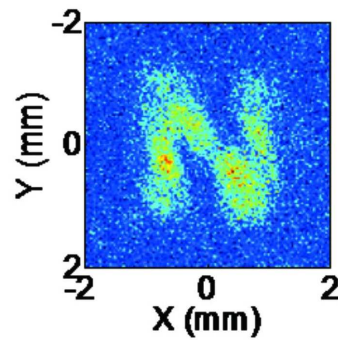
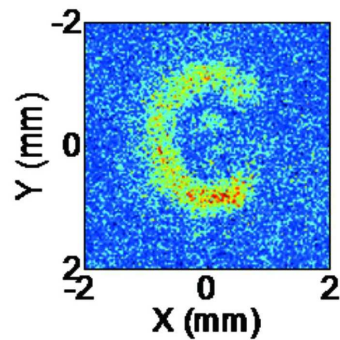
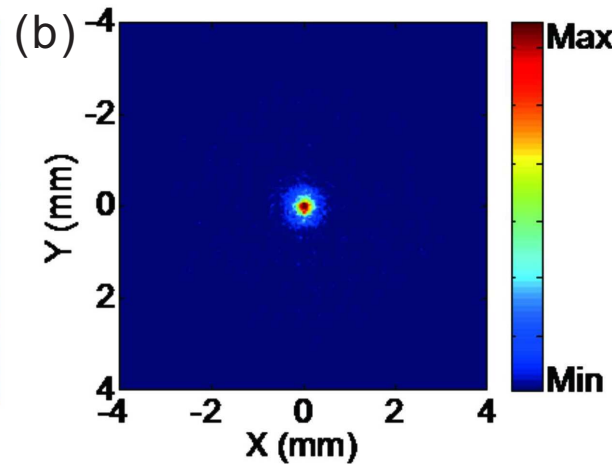
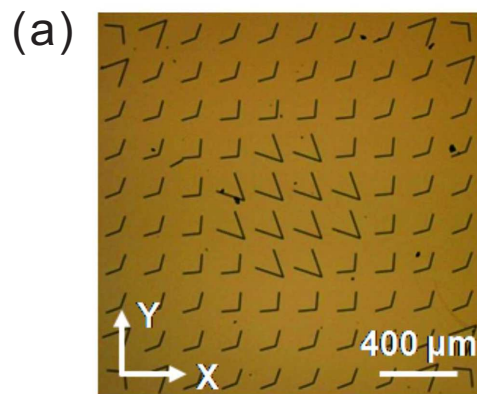
(a) Photograph of a part of the fabricated cylindrical lens. **(b)** Intensity distribution of the cross polarized light for the designed cylindrical lens. **(c)** Experimental measurement of the intensity distribution. **(d)** Intensity distributions along the white dashed lines shown in (b) and (c). **(e)** The line focus of the cylindrical lens on the preset focal plane in experiments.



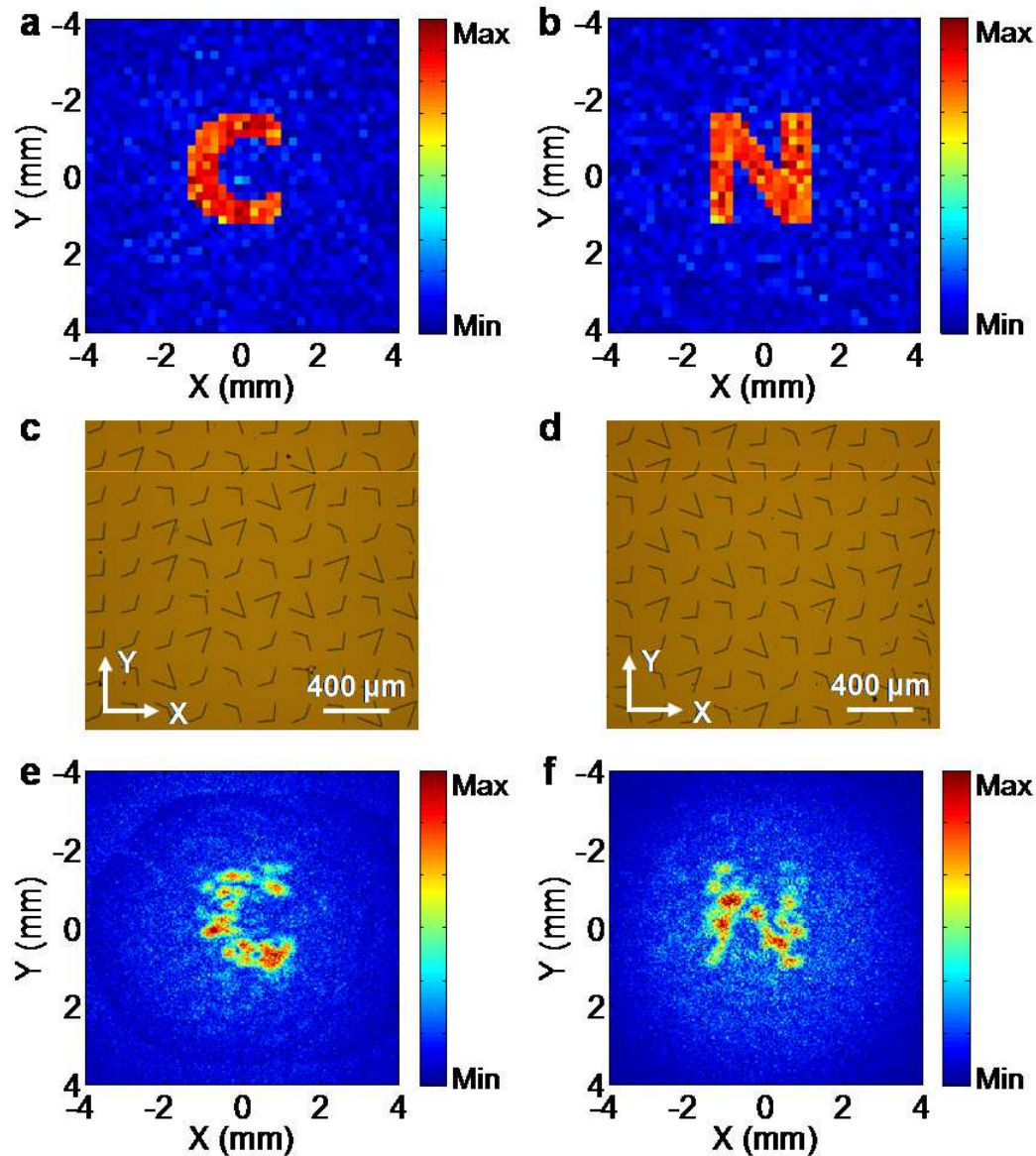
Dispersion of the cylindrical lens

Metasurface based devices

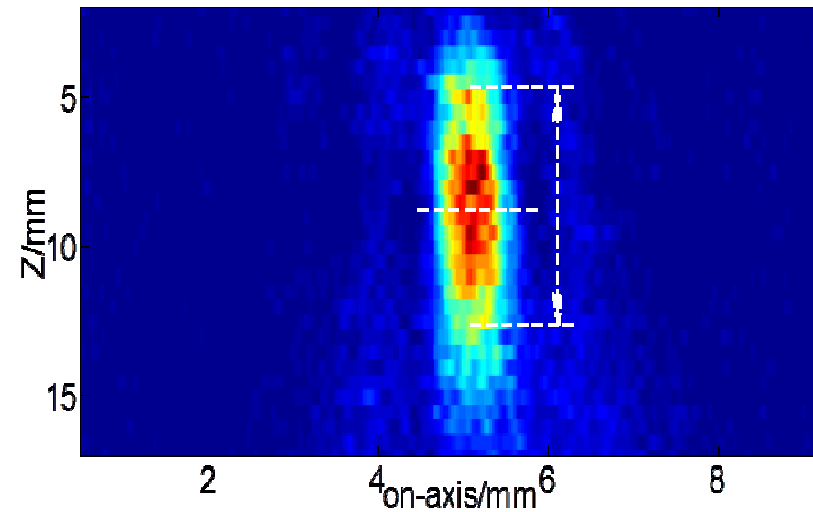
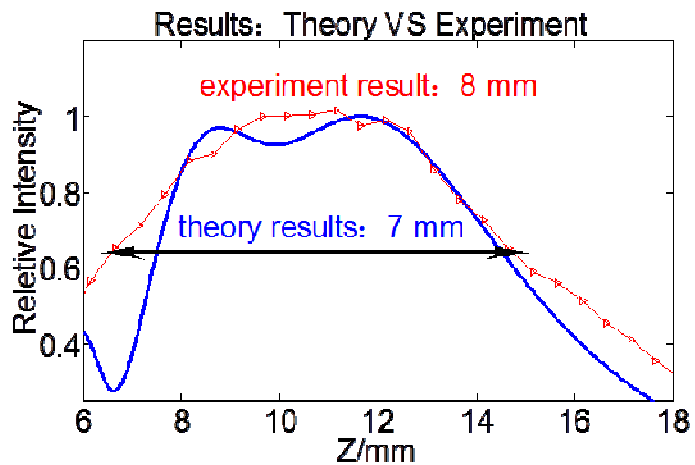
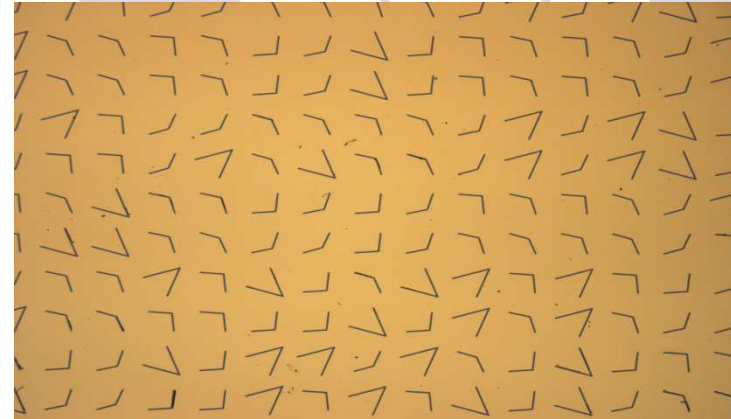
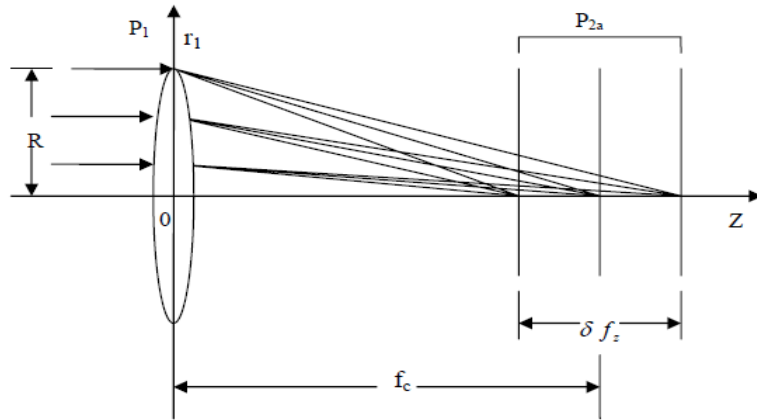
Spherical lens imaging



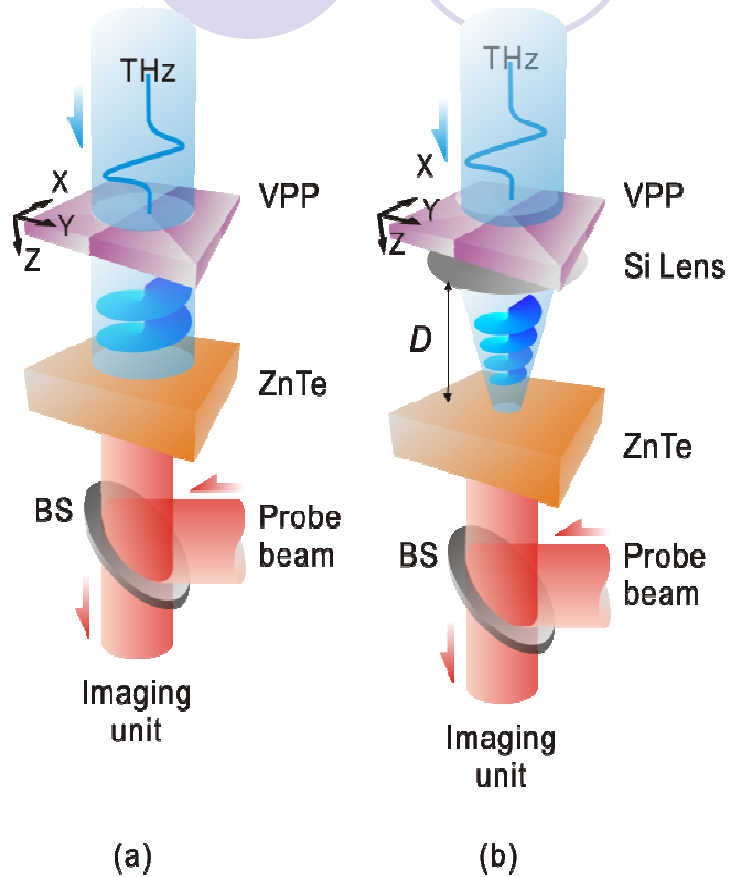
**The thickness of the lens
 is only 1/4000 of the
 wavelength!**



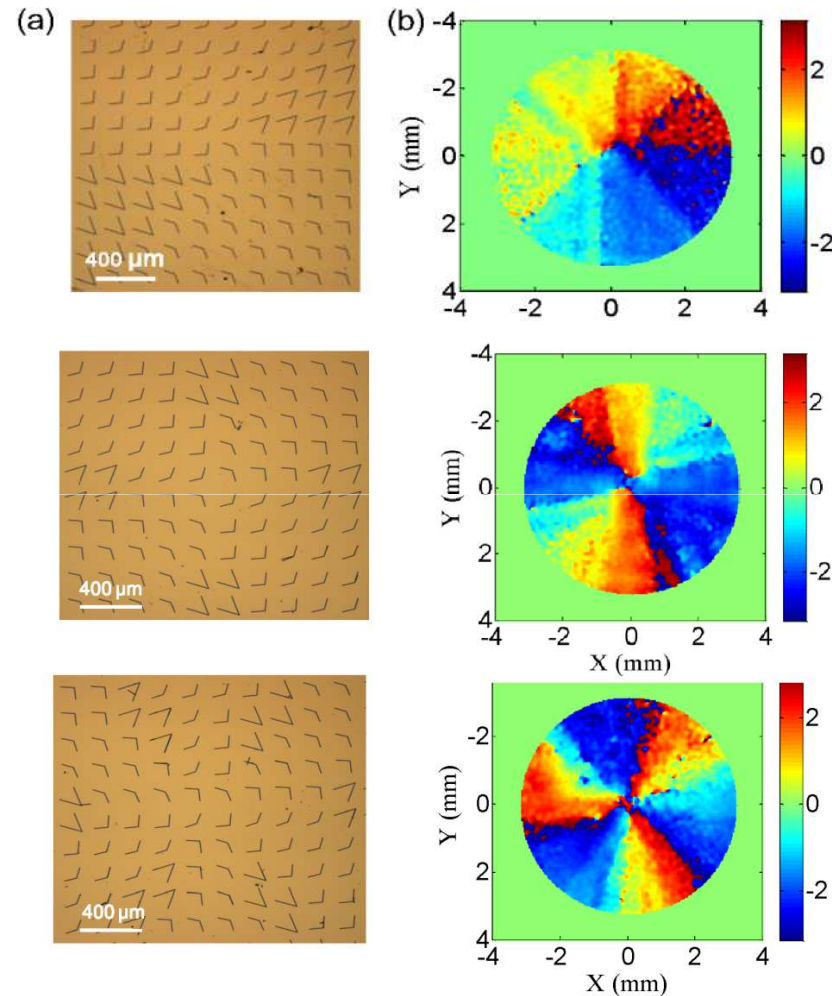
Ultrathin phase holograms for special optical field generation. **(a)** and **(b)** Desired images to be appeared on the plane which is 4mm away from the holograms. **(c)** and **(d)** Optical pictures of part of the ultrathin phase holograms for generating the desired images shown in (a) and (b), respectively. **(e)** and **(f)** Images generated by the holograms.



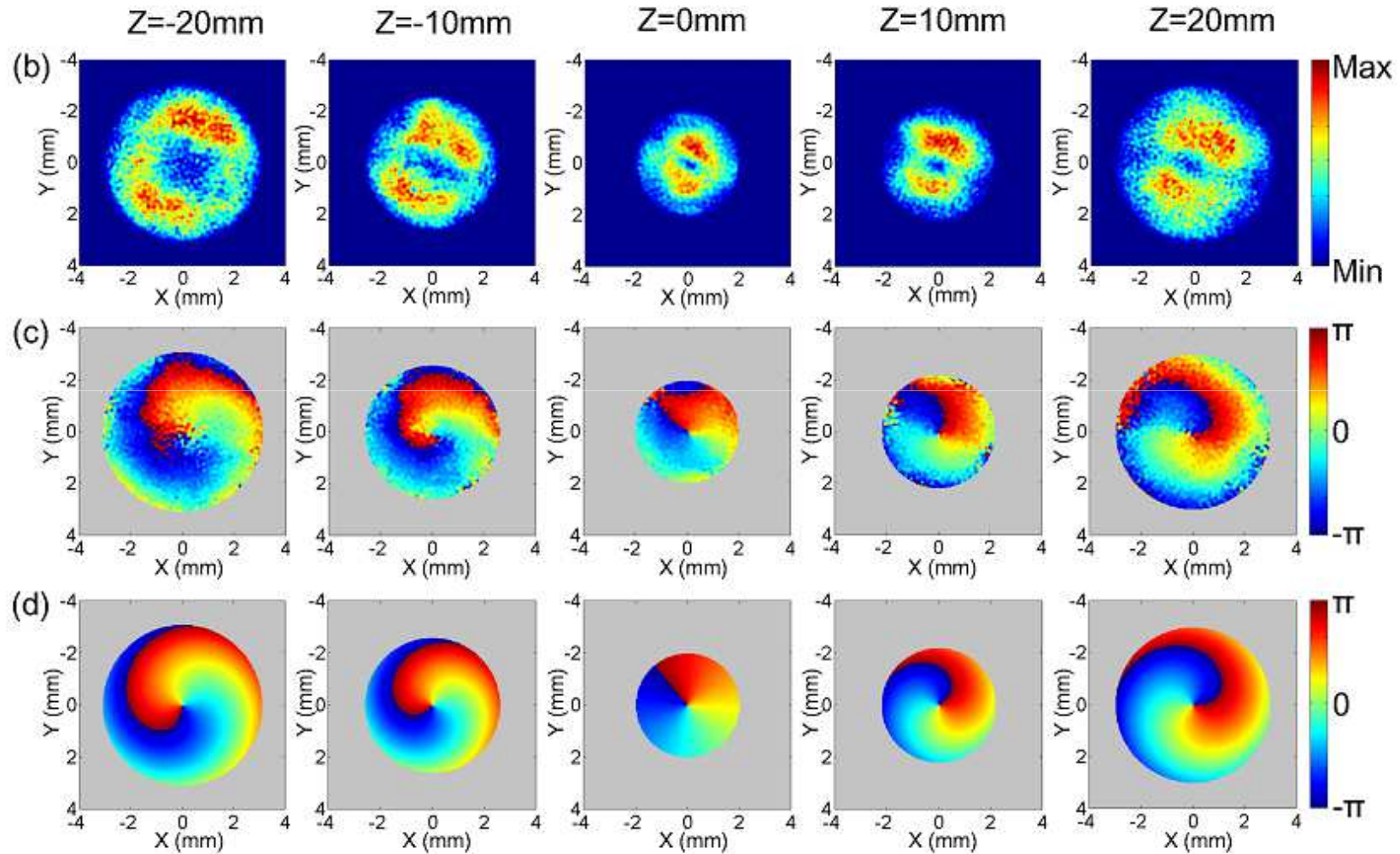
Ultrathin phase element for generating long focal length

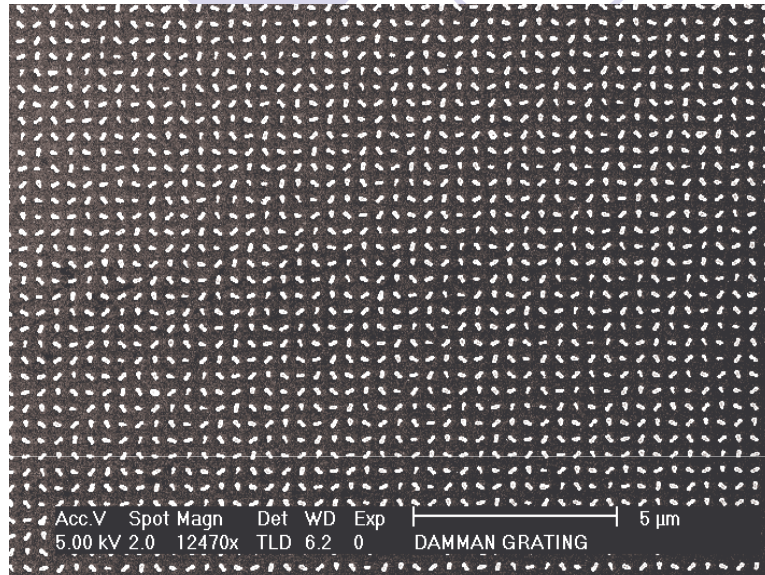


Experimental setup



The central region of the designed devices for $l=1, 2$, and 3 , and (b) corresponding optical vortex phase





Damman grating

Working wavelength: 750nm

Wavelength range: 650-1000nm



Size of device: 180 μm

Size of cell: 400nm

Focal length: 150 μm

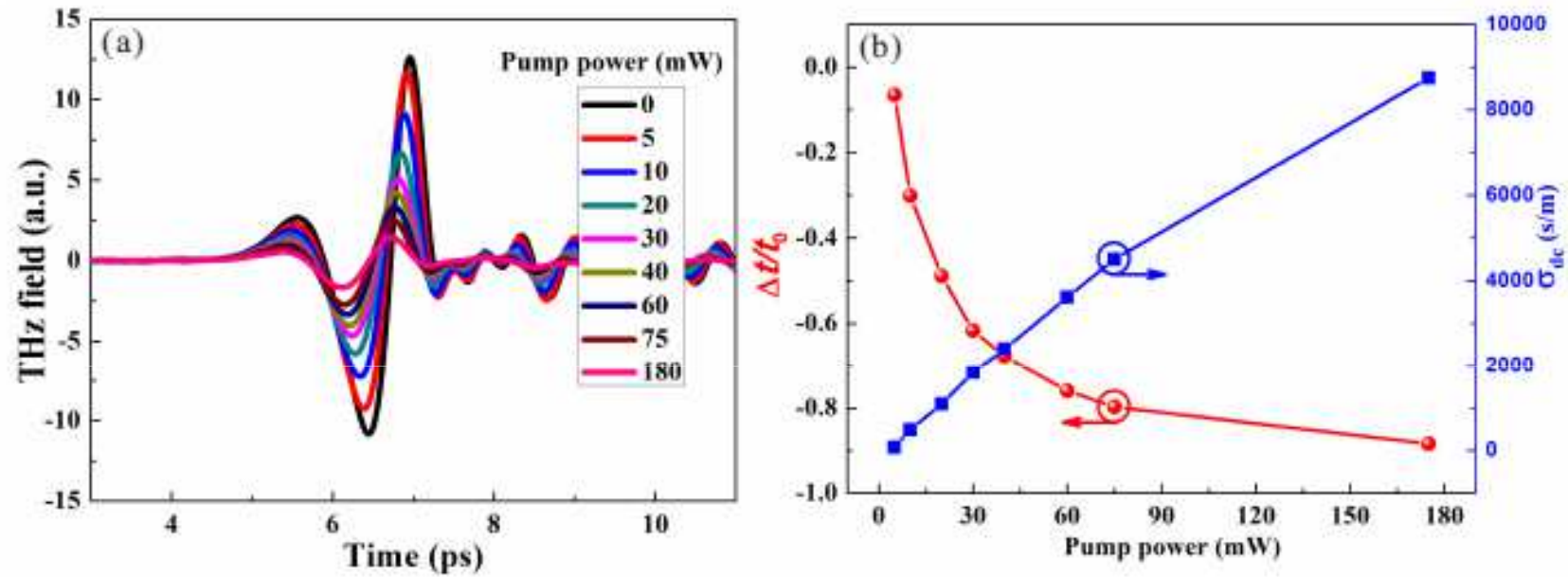
Typical size: 40nm

Ultrathin planar elements

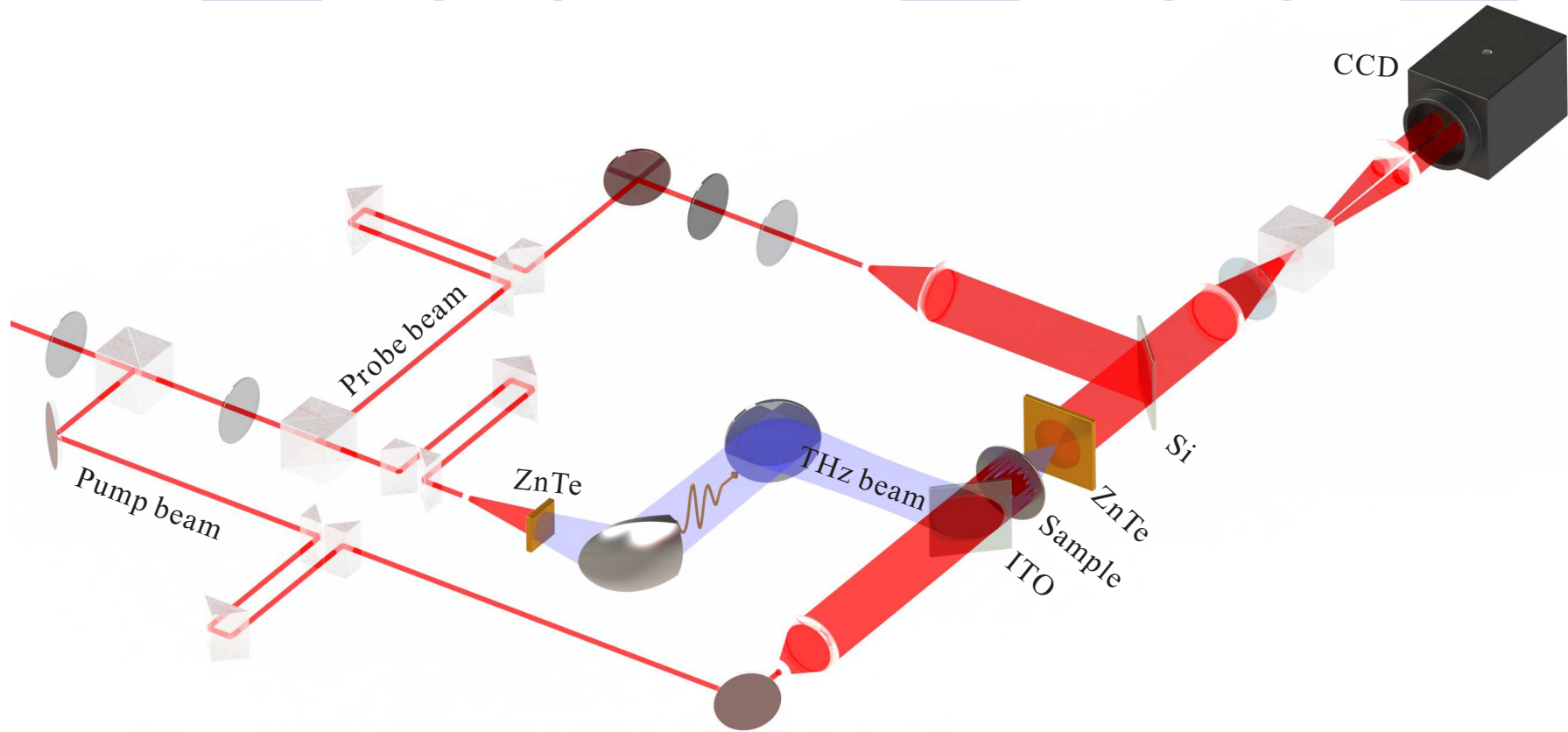
😊 thin, aberration free,.....

😞 low efficiency, function fixed

Active control of THz wavefront

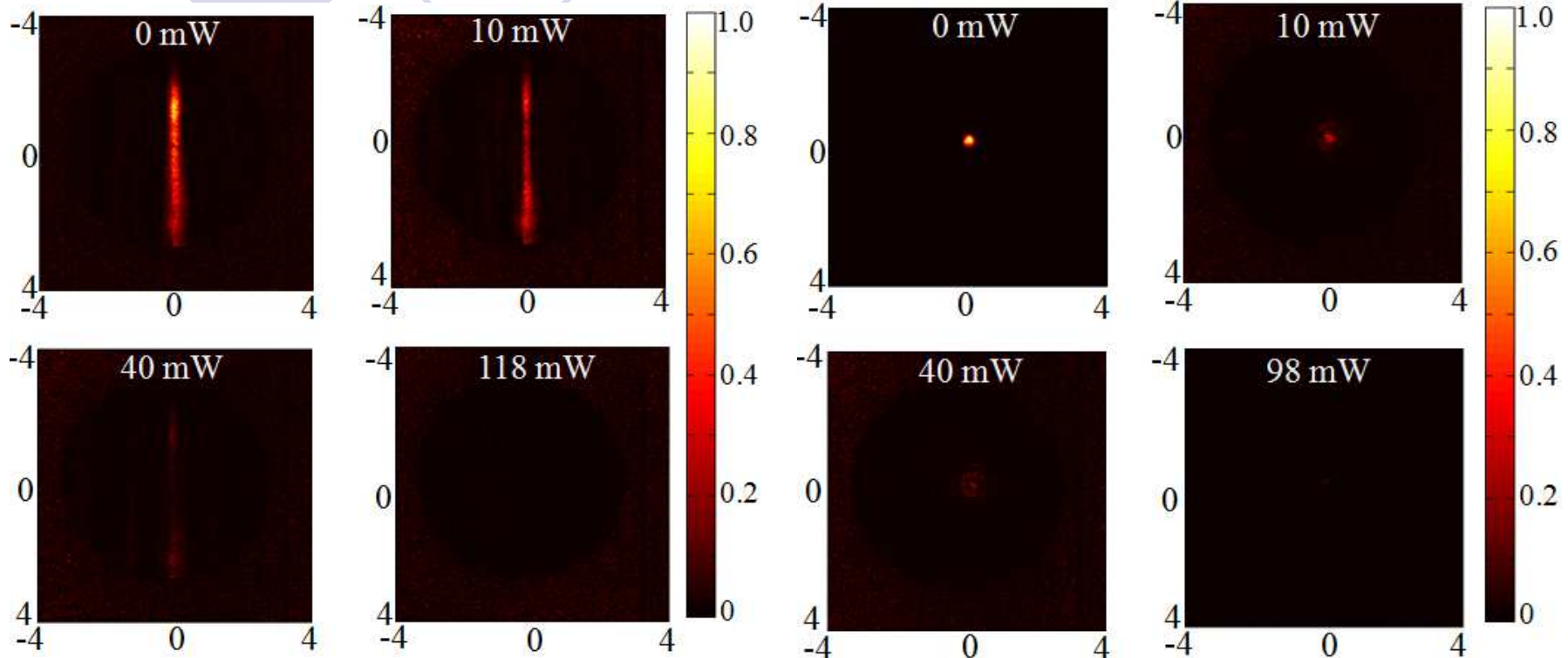


Variation of transmission and DC conductivity of Si under pump with different power.



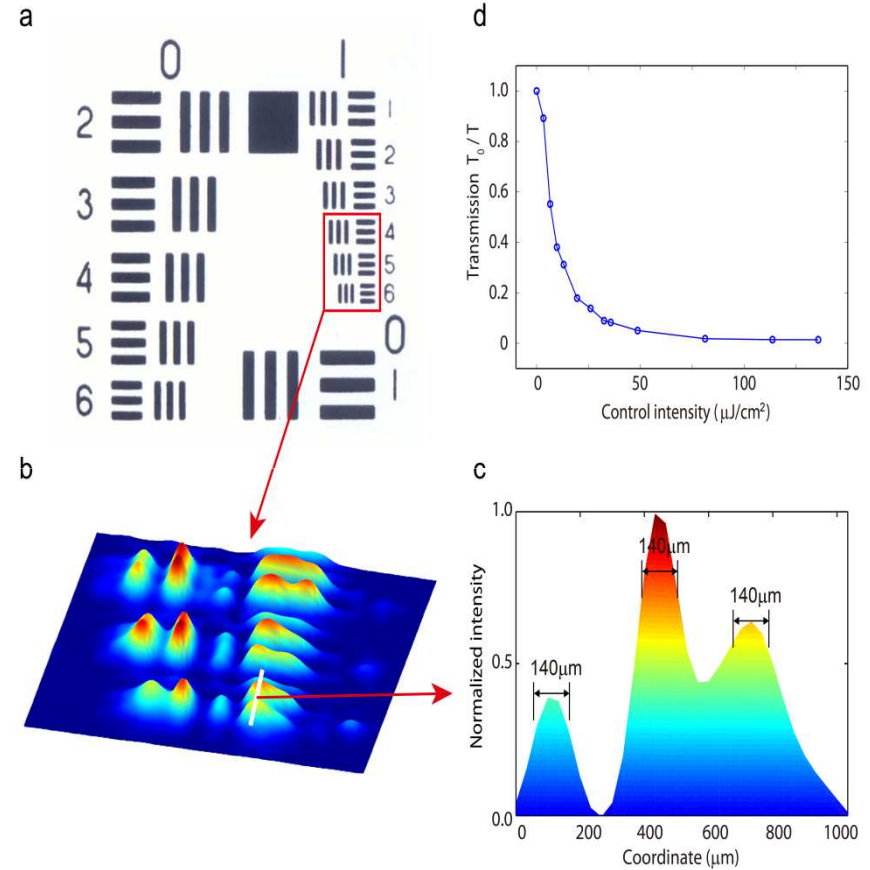
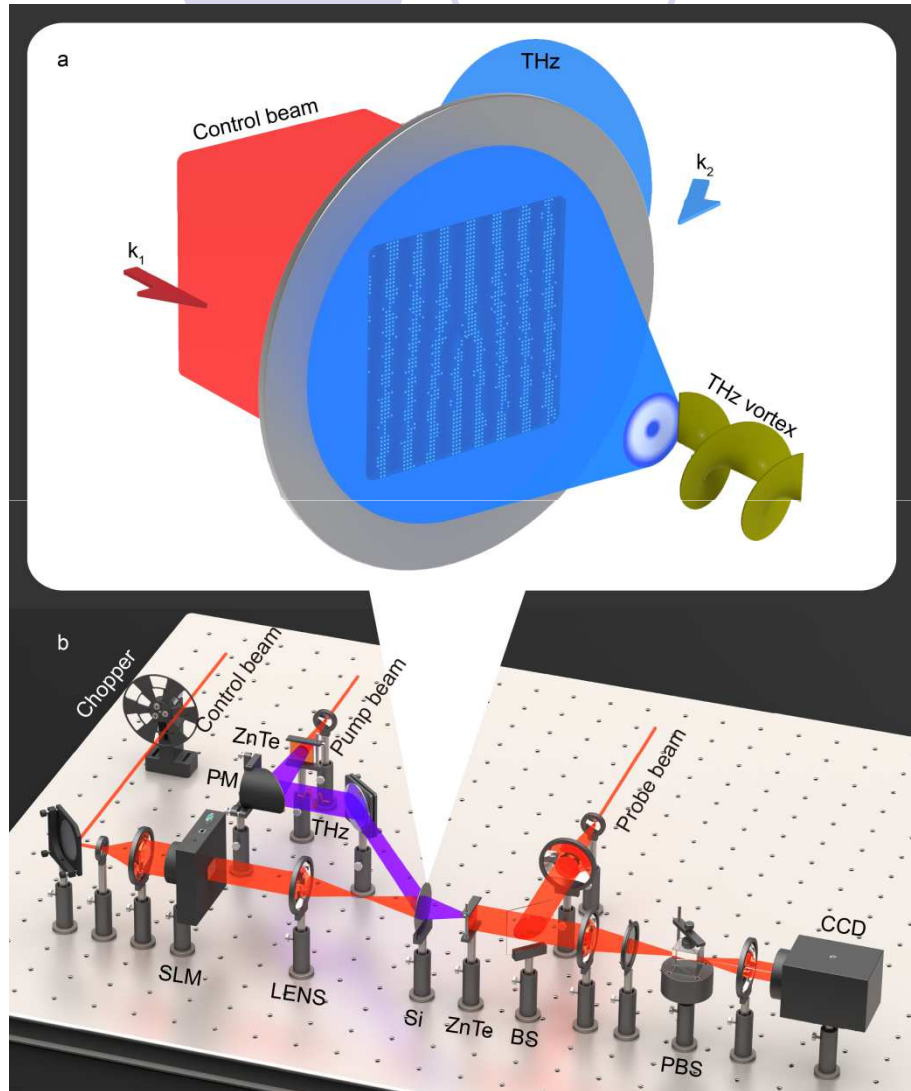
THz pump probe imaging system

Active control of THz wavefront

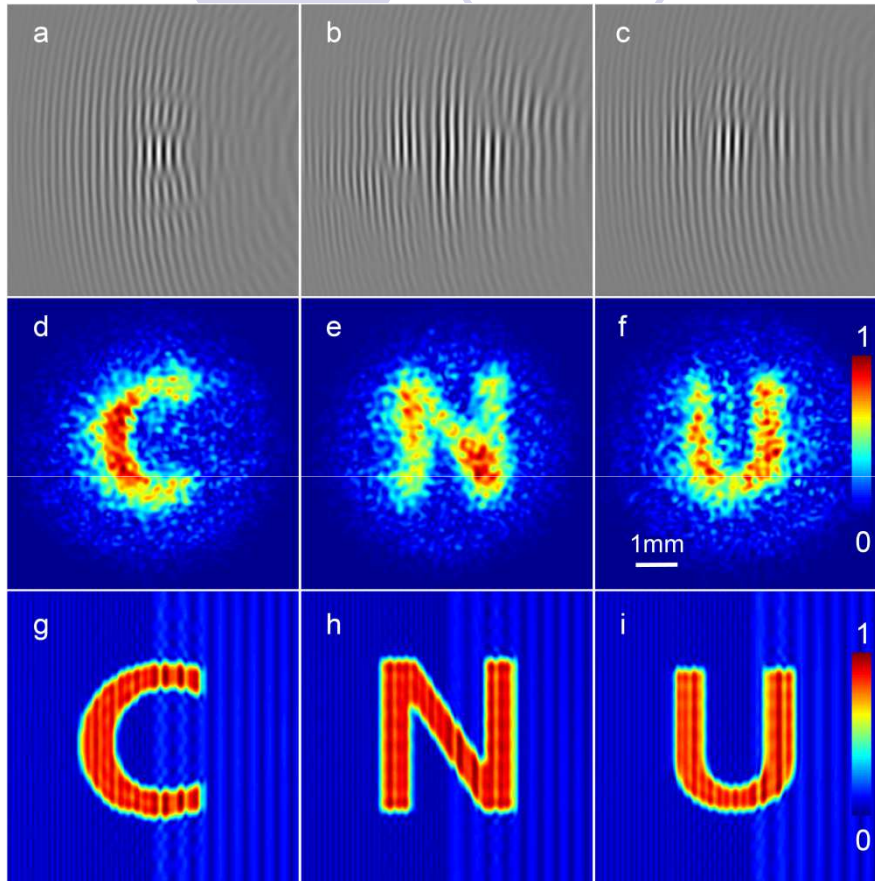


Cylindrical lens,
Modulation depth 98.3%

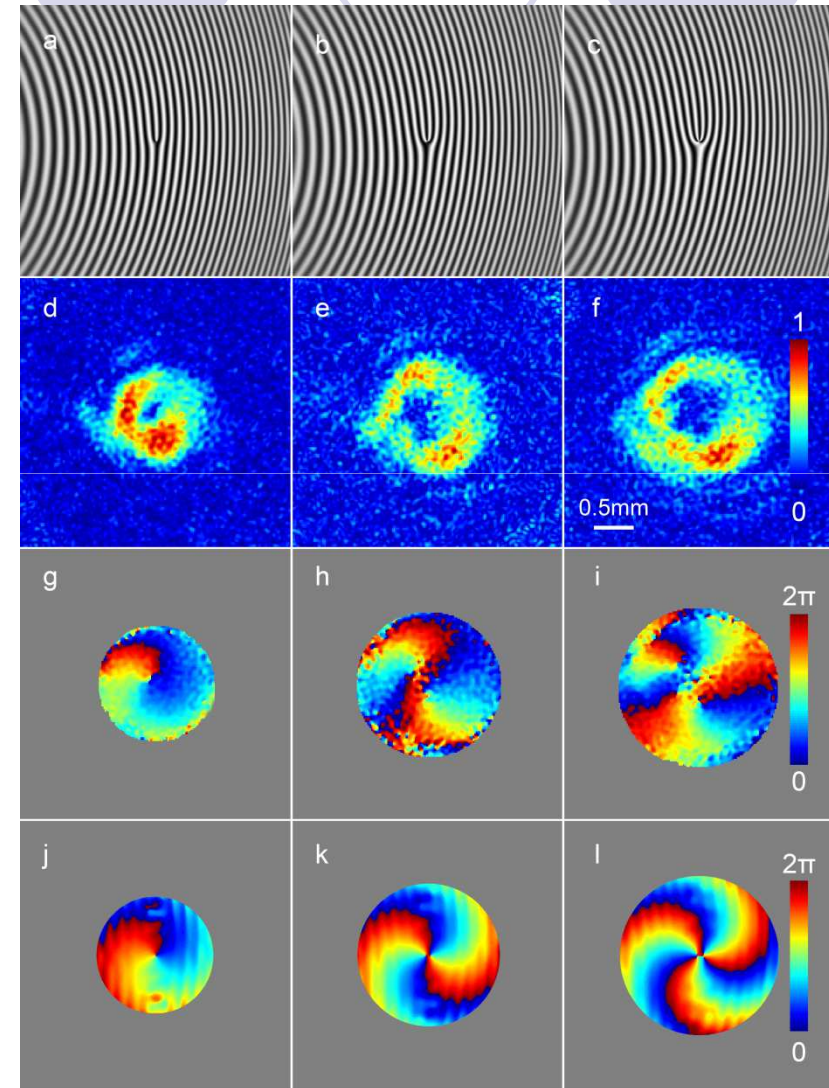
Spherical lens
Modulation depth 90%



Active optical controlled spatial THz modulator (STM)



THz offline holograph for desired pattern generation.



Conclusion:

◆ Ultrathin planar elements

Lens, holograms, diffractive phase elements...

◆ Characterization of ultrathin planar elements

Intensity, phase, polarization, wavelength...

◆ Active control of THz wavefront

Collaborated with

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**Thank you for
your attention!**

Planar Photonics with Metasurfaces

Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaginov

Metamaterials, or engineered materials with customarily designed, subwavelength-scale building blocks, allow us to control the behavior of physical fields in optical, microwave, radio, acoustic, heat transfer, and other applications with flexibility and performance that are unattainable with naturally available materials. In turn, metasurfaces—planar, ultrathin metamaterials—extend these capabilities even further. Optical metasurfaces offer the fascinating possibility of controlling light with surface-confined, flat components. In the planar photonics concept, it is the reduced dimensionality of the optical metasurface that enables new physics and, therefore, leads to functionalities and applications that are distinctly different from those achievable with bulk, multilayer metamaterials. Here, we review the progress in developing optical metasurfaces that has occurred over the past few years with an eye toward the promising future directions in the field.

With the recent advances in micro- and nanofabrication methods, one can now control the flow of light in a way that was not possible before. Metasurfaces (MMs) are engineered structures with minimally designed, nanostructured building blocks (“metatoms”). MMs allow us to build devices with responses to light, acoustic waves, and heat flows that are unattainable with naturally available materials (1–3). In the artificial patterns of metasurfaces, the propagation of electromagnetic energy can be defined by the spatial and spectral dispersions of the effective dielectric and magnetic properties. These synthetic structures offer the distinct potential to guide and control the flow of electromagnetic energy in an engineered optical space (2) and open the door to a number of applications that were previously considered impossible (4). We are no longer constrained by the electromagnetic response of natural materials and their chemical composition. Instead, we can tailor the shape and size of the structural units of a MM, tune the composition and morphology of the nanostructure, and achieve new, desired functionalities. The extraordinary properties of optical MMs and transformation optics (TO) devices (2), which were conceived by MMs, enable a negative refractive index, imaging with the nanometer-scale resolution, invisibility cloaks, efficient light antennas, nano-optics and quantum information applications (1–4).

Optical metasurfaces comprise a class of optical MMs with a reduced dimensionality that demonstrate exceptional abilities for controlling the flow of light beyond that offered by conventional, planar interfaces between two natural materials (5). Such two-dimensional (2D) and quasi-2D MMs provide us with the distinct possibility to fully control light with planar (or nearly

planar) MM elements and, thus, to realize “planar photonics.” Metasurfaces enable new physics and phenomena that are distinctly different from those observed in their 3D counterparts. Moreover, they are compatible with on-chip nanophotonic devices, which is of critical importance for future applications in optoelectronics, ultrafast information technologies, microscopy, imaging, and sensing.

A metasurface structured on the subwavelength scale in the lateral directions can be deterministic (i.e., periodic and aperiodic) or random. In practice, such a metasurface is represented by a patterned metal-dielectric layer that is very thin compared with the wavelength of the incident light and is typically deposited on a supporting substrate. The functionality of a device based on such a metasurface depends directly on the effective, surface-confined, optical dispersion. Effective optical properties, along with nonconventional far-field responses of ultrathin metasurfaces, for example, have been found to deviate from classical reflection and refraction laws (5, 6). Hence, the responses of metasurfaces cannot be inferred from the experimental responses for bulk materials. To design reliable flat photonic devices, a fundamental understanding of the extraordinary properties, as a function of the lateral dimensional features and the structural ordering, is required. There is a critical need to develop innovative theoretical, experimental, and fabrication approaches to unleash the power of functional optical metasurfaces.

In a long-wavelength regime (from radio to terahertz waves), surface-confined metallic antennas arrays, or “metaslabs” (7–9), containing multiple antenna elements have already been successfully used for communication applications (10–12) or as highly confined cavity resonators (11, 14). Similar to optical metasurfaces, the antenna element is such “refractor” (13) and “transmitter” (12) also act as phase-controlling resonators for manipulating the direction in which radio or microwave signals are received or broadcast. Nevertheless, the desired phase shifts in

both field and transmission are obtained with the dimensions of resonant elements and array periods of a magnitude comparable in size to the incident or transmitted free-space wavelength (15).

The importance and power of planar photonics was demonstrated earlier for the specially designed case of planar chiral elements (16–19). The recently discovered generalized Snell’s law suggests a way toward ultimate control of light propagation (5). As demonstrated by Yu *et al.* (3), special nanostructures—metasurfaces—create phase discontinuities for light propagating through the interfaces and, distinctly, change the flow of reflected and refracted light, as similarly demonstrated for the metal-dielectric (mid-IR) wavelength of 8 μm (5). This phenomenon has recently been extended to the near-IR wavelength region (6), where it was also shown that the effect is robust and broadband. With these new approaches, metasurfaces could be used to fully control all light parameters, including frequency, phase, polarization, momentum, and angular momentum (20–23). Metasurface-based optical vortex plates (27), aberration-free and ultrathin flat lenses, and antennas at telecommunication wavelengths (24) have recently been demonstrated. Ni *et al.* also reported that extremely thin (30 nm) and very small (2 μm in radius) metasurfaces based on Fabry-Pérot complementary metamaterials (V-shaped slots in a metal sheet) can be used for the extra-strong focusing of light (with a focal length as short as 2.5 μm) in the visible wavelength range (25). In addition, ultrathin synthetic phase lenses have also been proposed (26).

Another recent demonstration showed that 3D effects on light propagation can be obtained without the need for complex inclusions in bulk MMs. Instead, planarized, broadband, bianisotropic MMs consisting of stacked natural anisotropy can be used (27). These natural anisotropy contain a tailored rotational twist and were shown to constitute an ultrathin, broadband circular polarizer that can be directly integrated within nanophotonic systems (27). Planarized metasurfaces have also been proposed and realized as quarter-wave plates (28, 29). Metasurfaces can be used to effectively couple propagating waves to surface waves (30), which could be of great importance for on-chip nanophotonic applications. Kang *et al.* have also shown that thin, U-shaped aperture antennas can be used to compactly convert circularly polarized light into its cross-polarized counterpart (31). As shown by Shi *et al.* (32), nanostructure metasurfaces can generate optical beams with desirable orbital angular momenta (OAM) [see also (33)]. Simon *et al.* have reported that specially engineered metasurface-based OAM states can be used also for high-efficiency quantum cryptography and a new quantum-key distribution protocol, exploiting, for example, the nonlocal properties of the Fock state sequence (34).

Finally, it has been shown that so-called flat and multilayer MM structures can be used for

Metasurface based devices

in a metal sheet) can be used for the extra-strong focusing of light (with a focal length as short as 2.5 μm) in the visible wavelength range (25). In addition, ultrathin terahertz planar lenses have also been proposed (26).

26. D. Hu *et al.*, <http://arxiv.org/abs/1206.7011v1> (2012).

27. Y. Zhao, M. A. Belkin, A. Alù, Twisted optical metamaterials for planarized ultrathin broadband circular polarizers. *Nat. Commun.* 3, 870 (2012).

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