

## Abstract

Metasurfaces have attracted large interest in recent years due to their relatively simple fabrication, compact design, and ability to control the wavefront of incident light. Ohmic loss attributed to bulk metal metamaterials are not a primary issue, whereby the meta-atom or plasmonic structure is typically only as thin as a fraction of the operation wavelength. Numerous novel applications have been demonstrated by metasurfaces, including an ultrathin metasurface flat lens, and 3D holography.

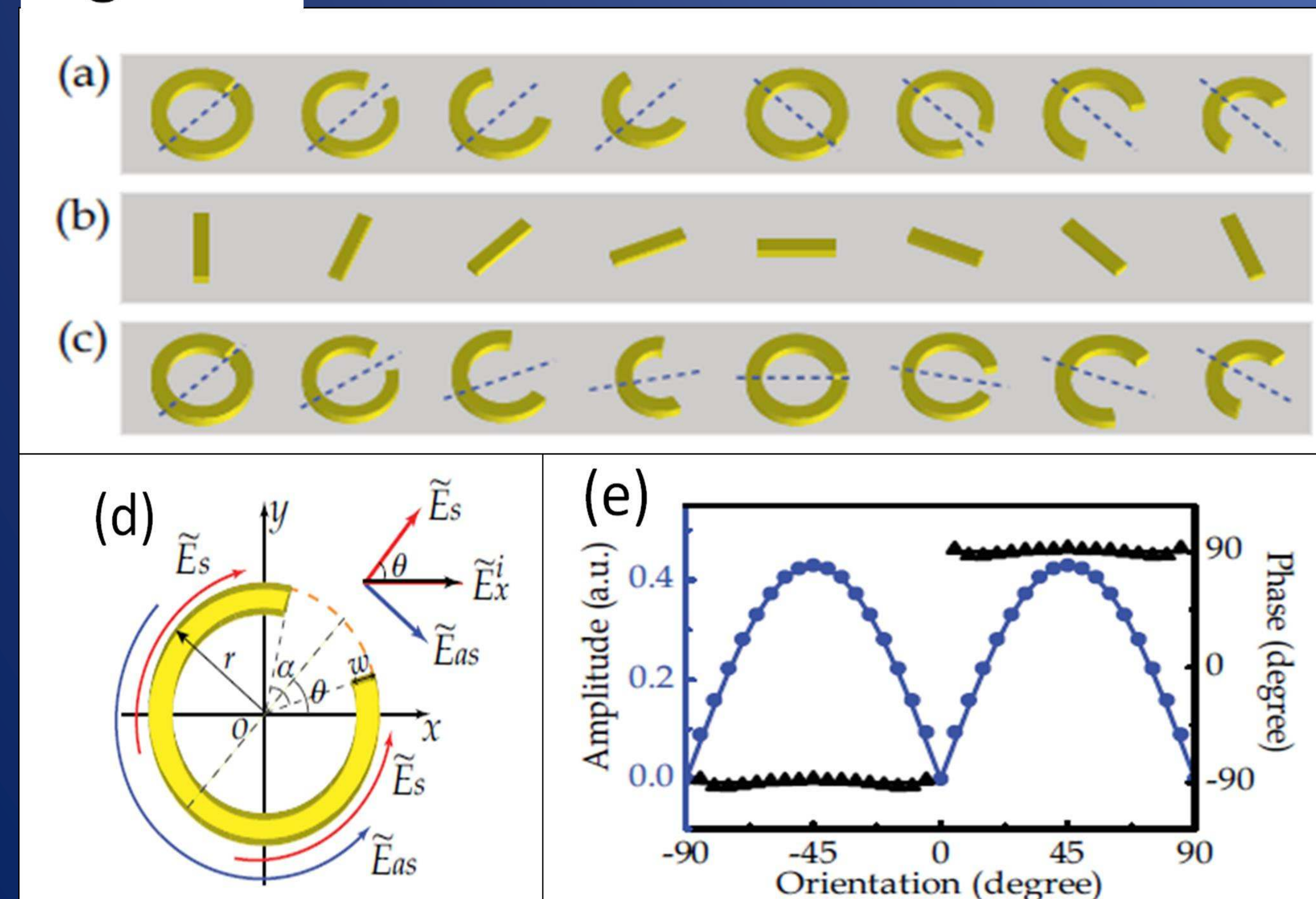
*Here, by combining the freedom of both the structural design and the orientation of split ring resonator antennas, we demonstrate Terahertz metasurfaces that are capable of controlling both the phase and amplitude profiles over a very broad bandwidth at ~1THz under linearly-polarised incidence. As an example, we show that these phase-amplitude metasurfaces can be engineered to control the diffraction orders arbitrarily.*

## Background

- We combine the functionalities of two types of metasurface operating under linearly-polarised incident light; a **Split-Ring Resonator (SRR)** type (Figure 1a), where the geometry of the SRR is adjusted to **control phase**; and a **nanorod type** (Figure 1b), which **controls the amplitude** of light dependent upon the rotational orientation – to give a combined metasurface similar to that shown in Figure 1c.
- This metasurface operates under a linear cross-polarisation scheme, whereby the transmitted beam is orthogonal to the incident polarisation. The symmetry line of each antenna is along  $\pm 45^\circ$  to maximise cross-polarisation conversion from the incident horizontal or vertical polarisation (Fig 1d).
- Amplitude** can be smoothly varied by a rotation,  $\theta$ , of the SRR symmetry axis with respect to the incident linearly polarised light (in this case, x-polarised), and the **phase** controlled by changing the SRR geometry – namely the arm width ( $w$ ) and the open angle ( $\alpha$ ), as shown in Figure 1d, also.
- The generated y-polarised scattered field  $\tilde{E}_y^s$  can be written as,

$$\tilde{E}_y^s = \frac{1}{2} \tilde{E}_x^i \sin(2\theta) (A_s e^{i\phi_s} + A_{as} e^{i\phi_{as}}) = \tilde{E}_x^i A e^{i\phi}$$

Figure 1

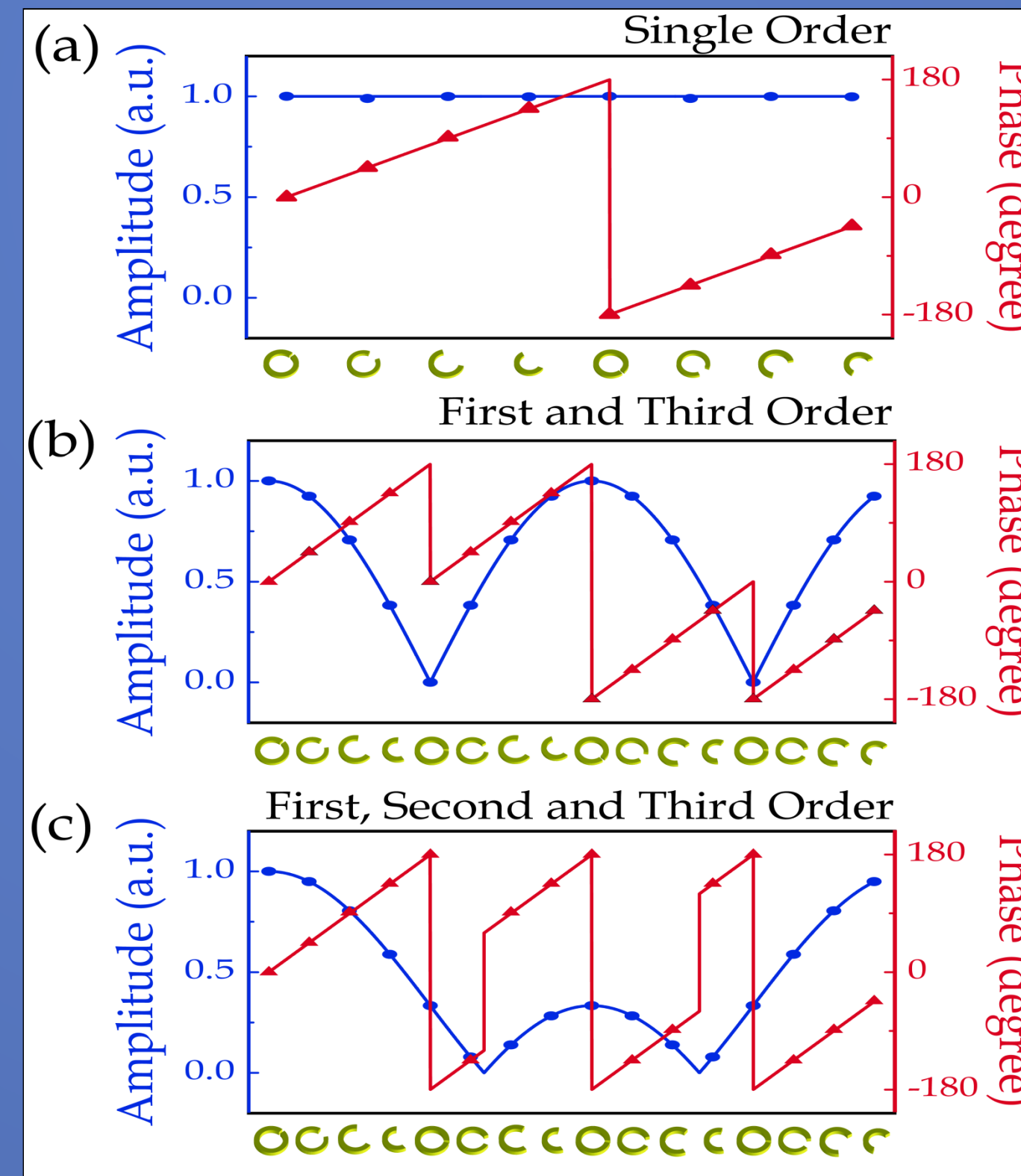


- Simulated amplitude and phase variations of a C-shaped antenna are shown in Fig 1e for varying  $\theta$  at 0.63THz, with  $(r, \alpha) = (34\mu\text{m}, 11^\circ)$ . It is clear that the **amplitude varies as  $|\sin(2\theta)|$** , whilst the phase is constant apart from a **phase jump of  $\pi$**  occurring at  $\theta = 0$ .
- In general, to generate a grating with desired diffraction order amplitudes  $A_m$ , the transmission through the grating is expressed as,

$$t(x) = A(x) \exp[i\phi(x)] = \sum_m A_m \exp(-i2m\pi x/d)$$

- Three metasurface designs for generating different diffraction orders are given in Figure 2, with Fig 2a, 2b and 2c being **1 order**, **2 orders**, and **3 orders**, respectively. All these metasurface designs use four different antenna geometries, whose phase spans evenly in steps of  $\pi/4$ . The '1 order' metasurface has 8 antennas, and the '2' and '3' order metasurfaces both consist of 16 antennas, all spaced at  $80\mu\text{m}$ .

Figure 2



## Results

- The samples A-D were made by standard photolithography techniques and metal lift-off process, and had antenna spacings of  $80\mu\text{m}$ ,  $100\mu\text{m}$ ,  $80\mu\text{m}$ , and  $100\mu\text{m}$ , respectively.
- A fiber-based angular resolved terahertz time-domain spectroscopy (THz-TDS) is used to characterise the diffraction orders of the samples between 0.4 and 1.0 THz, at normal incidence.

- Sample A** – **Single** diffraction order (Fig 3c)
- Sample B** – **Two** diffraction orders (Fig 3d)
- Sample C** – **Two** diffraction orders (Fig 3e) and optical image (Fig 3a).
- Sample D** – **Three** diffraction orders (Fig 3f) and optical image (Fig 3b).

- It is clear that the metasurfaces have broadband operation, even though they were designed at 0.63THz, using Finite Difference Time Domain (FDTD) methods (CST™ Microwave Studio).

## Simulations

- Numerical simulations were carried out in CST Microwave Studio for the 4 samples (A-D) that were fabricated.**
- A Terahertz beam incident from the substrate side onto the metasurfaces. The cross-polarised electric field distributions at 0.8THz are seen in Fig 4a,b,g,h, for samples A-D, respectively.
- Fig 4a clearly shows a uniform anomalous transmitted wave, agreeing with the single diffraction order sample design. Figure 4b, e, f show results for two (samples B & C) and three (sample D) orders.
- The problem is that for two or more orders, the wave is no longer uniform – therefore, we apply a Fourier Transform to the field distributions at a distance of  $900\mu\text{m}$  from the metasurface – given in Fig 4c,d,g,h, and clearly correctly showing the dominance of the diffraction orders.
- These FT results agree well with the experimental measurements, and show clearly defined arbitrary diffraction orders.

Figure 3

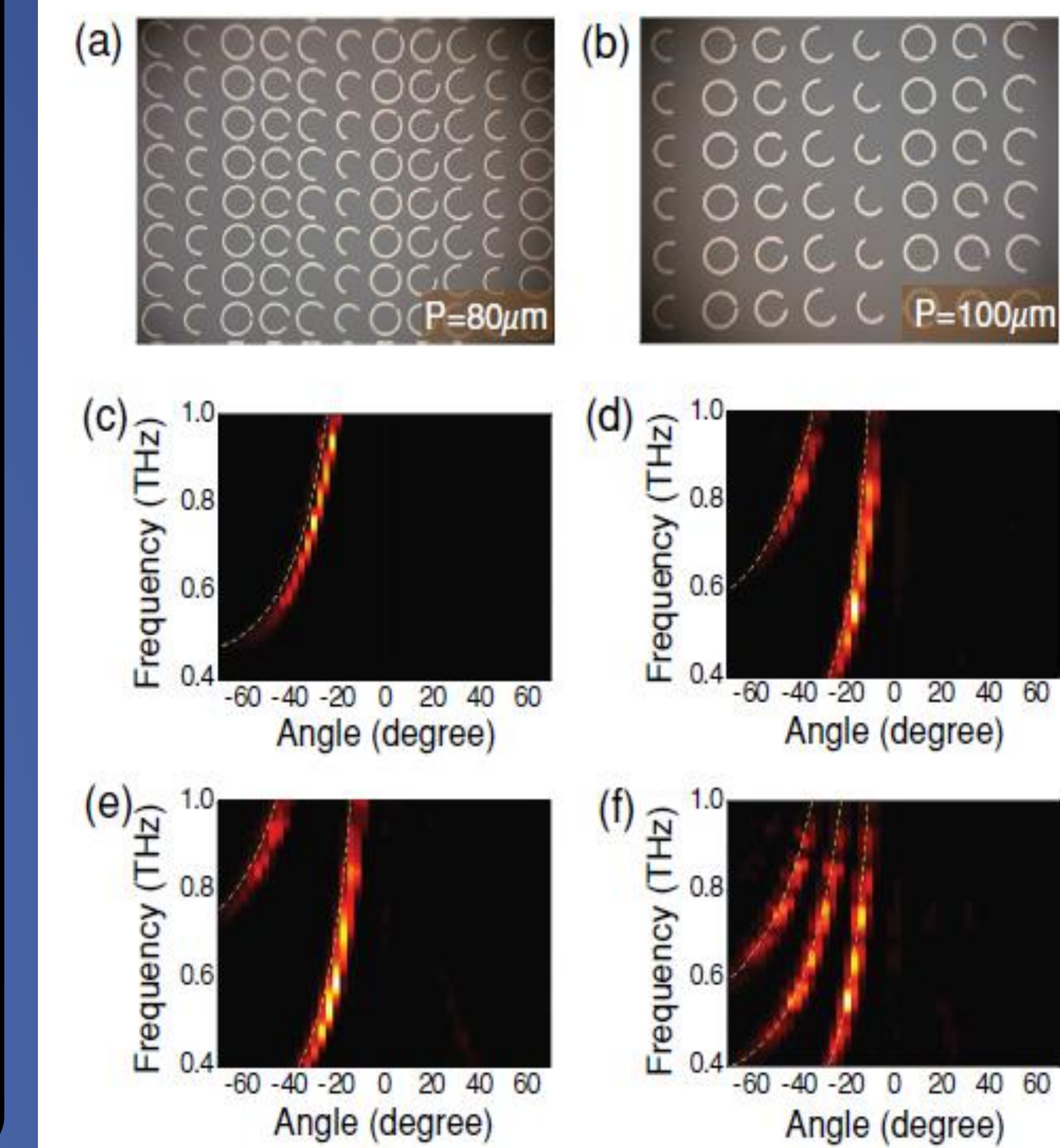


Figure 4

