Reconfigurable Fourier Filtering Imaging Bilayer Metasurface

Ping Sun[1]

Michele Cotrufo[2]

1 The Institute of Optics, University of Rochester, Rochester, NY, USA

2 The Institute of Optics, University of Rochester, Rochester, NY, USA

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Abstract: This paper demonstrates one bilayer Silicon metasurface with rhombus-arranged air-holes, enabling switch between 0.1-0.5 NA 360° Azimuthal 3D edge detection with high polarization-insensitivity and isotropy and 1D center blur & denoising by air gap tunning.

Fourier signal filtering remains a continuously prominent topic across various disciplines, including signal processing, imaging, and computational signal analysis. Traditional methods typically rely on spatial filters to modify spatial frequency components, but such devices are generally fixed in design and limited to single functionalities. Leveraging the versatile reconfigurability of flat photonics, this paper introduces a bilayer metasurface structure capable of achieving multiple filtering functionalities at a single operating wavelength, shown in Figure 1. Specifically, through tunning the air gap between two layers, the device can achieve switching from 360° Azimuthal 3D edge detection with high polarization-insensitivity and isotropy to 1D center blur & denoising effect for noisy image input. This work is among the first to achieve such a functional switch using flat photonics, laying the foundation in computational metasurfaces to perform multi-order derivative operations for imaging applications.

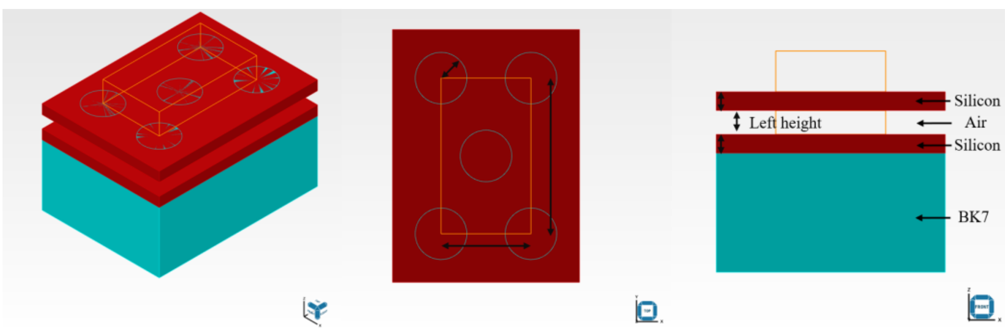


Figure 1 Structure. Bilayer silicon transmissive metasurface with rhombus-arranged air holes, presented in three perspectives: 3D view, top view, and side view, displayed from left to right. The angle between each air hole is 60 degree. Through tunning left air gap height, it can achieve different filtering functionalities.

To achieve edge detection of the input image, the metasurface's transfer function must strongly suppress the central spatial frequencies in the Fourier-transformed input image while allowing high transmission of other spatial frequencies. In contrast, center blur operates by performing the opposite effect. Thus, it is essential to design a transmissive, reconfigurable metasurface whose transfer function can be adjusted through specific tuning techniques to meet the requirements for both edge detection and center blur. Based on the pervious edge detection metasurface, the metasurface is firstly split into bilayer to introduce air gap tunning, and Figure 2 (a) sweeping the spectrum across the incident angle. This result defined the initial center blur condition, where at normal incident the transfer function can suppress the spatial signal to <0.1 level, and the device working wavelength. Through Azimuthal angle sweeping, Figure 3 (a, b) shows the transfer function of the metasurface for edge detection. To expand the functionality to center blur, the left gap sweeping is necessary, shown in Figure 4. It achieves center blur & denoising at larger left height under the same working wavelength, which is based on the cavity resonance of the bilayer. Figure 3 (c, d) shows the transfer function of the metasurface for center blur. Based on the switch of transfer function via gap tunning, Figure 5 shows its edge detection and center blur & denoising for 1D unpolarized input fringes image with 30-degree FOV. The edge detection actually does not limit in 1D but can work well in 2D edge detection functionality, which is shown in Figure 6 with 30-degree FOV.

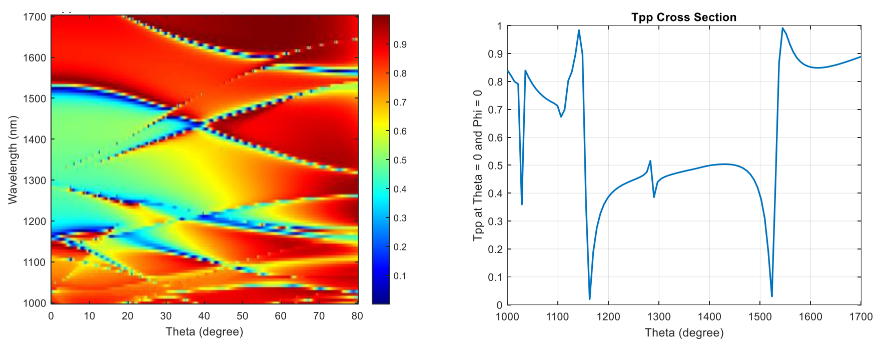
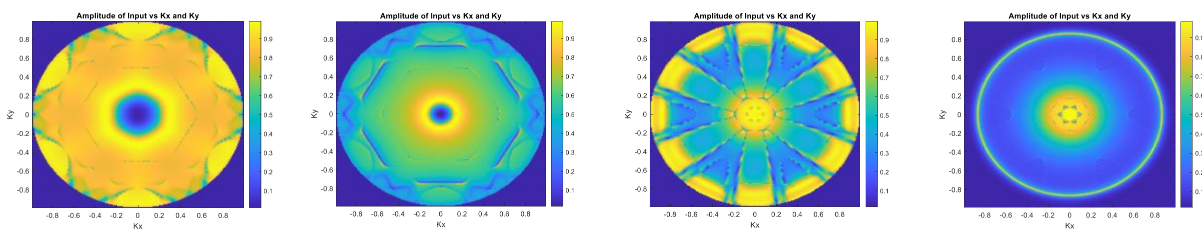


Figure 2 Incident θ Angle Sweeping Spectrum @ $\phi = 0°$: (Left) Transmission of p-pol with p-pol input with certain initial air gap (Right) Cross-section spectrum of Left plot at $\theta = 0°$ $\phi = 0°$



(a) (b) (c) (d)

Figure 3 Metasurface Transfer Function @ NA 80°: (a,c) Transmission of p-pol with p-pol input, (b,d) Transmission of s-pol with s-pol input

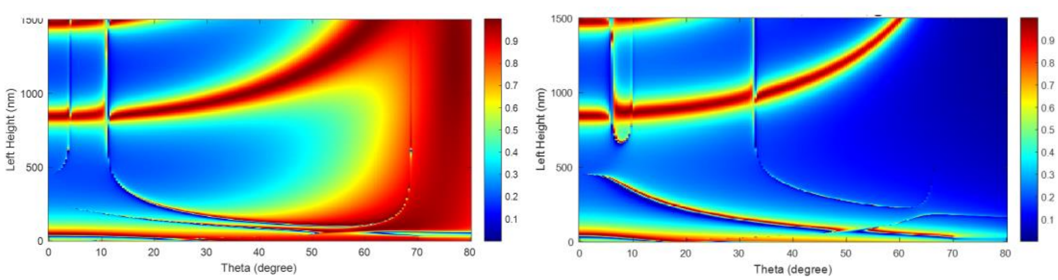


Figure 4 Angle Spectrum with left height @ $\phi = 0°$: (Left) Transmission of p-pol with p-pol input, (Right) Transmission of s-pol with s-pol input

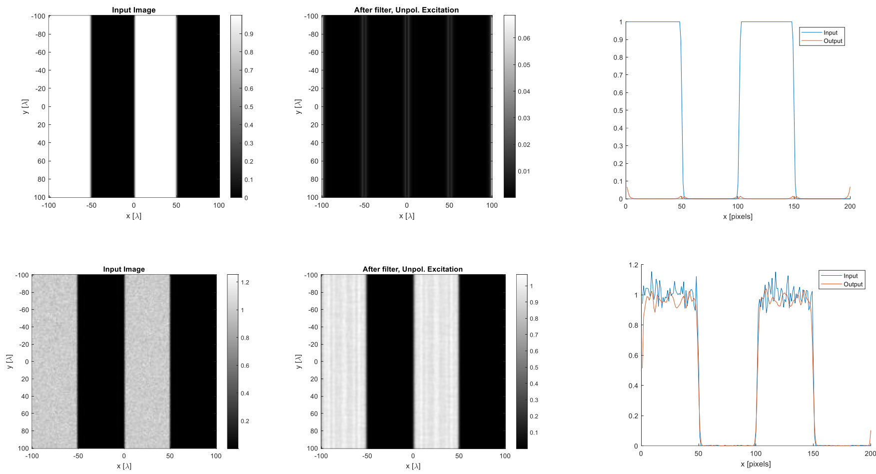


Figure 5. 1D Functionality Plots: Upper row from Left to Right: Initial image, Output after metasurface, x-cross section of output, for edge detection, Lower row from Left to Right: Initial noisy image, Output after metasurface, x-cross section of output, for center blur and denoising. These two functionalities are achieved under the same device and working at one wavelength and switched via gap height tunning.

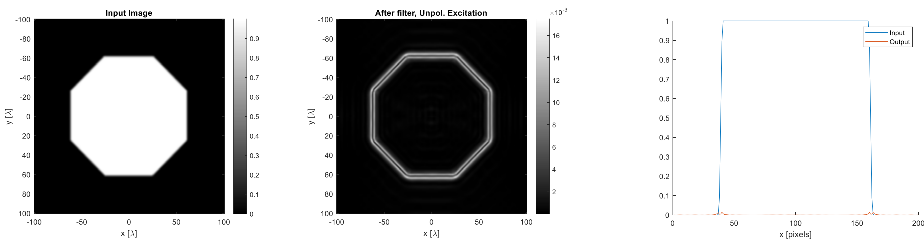


Figure 6. 2D Functionality Plots: from Left to Right: Initial image, Output after metasurface, x-cross section of output, for edge detection

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[2] Cotrufo, M., Arora, A., Singh, S., & Alù, A. (2023). Dispersion engineered metasurfaces for broadband, high-NA, high-efficiency, dual-polarization analog image processing. *Nature Communications*, 14, 6290.

[3] Komar, A., Aoni, R. A., Xu, L., Rahmani, M., Miroshnichenko, A. E., & Neshev, D. N. (2021). Edge Detection with Mie-Resonant Dielectric Metasurfaces. *ACS Photonics*, 8(3), 864–871.