Image Differentiation with Incoherent Light Using Angle-Sensitive Plasmonic Photodetectors

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Abstract: We use specially designed plasmonic photodetectors to develop a new method for image differentiation that can produce edge-enhanced images without external optical elements and under incoherent illumination, unlike traditional optical spatial filters. © 2022 The Author(s)

1. Introduction

Image differentiation by spatial filtering is a key image processing function for multiple applications in microscopy, photography, and computer vision. It can be used to enhance the edges of any object in the field of view for image sharpening as well as segmentation, to produce a highly compressed image that is easier to transmit and process. In fact, this idea is exploited in the initial stage of the visual recognition process, both in nature and in computer-based algorithms for image classification such as convolutional neural networks (CNNs). Highly complex spatial filtering operations can of course be implemented in the electronic domain, but require significant processing power and bandwidth which can severely limit their adoption in mobile edge-computing applications. Optical spatial filtering techniques represent a promising approach to overcome these limitations, but traditional systems based on Fourier optics tend to be quite bulky and provide limited functionality under incoherent illumination. As a result, significant research efforts are ongoing to perform similar operations with compact nanophotonics-based devices [1].

In this work we present a novel approach for optical spatial filtering based on specially designed directional image sensors. Specifically, we use photodetectors coated with a plasmonic metasurface that only allows for the detection of light incident along a small, geometrically tunable set of directions. These metasurfaces have been developed in recent work focused on a different application, i.e., planar lensless compound-eye vision with ultrawide field of view [2]. Similar devices can also be used as optical spatial filters, based on the notion that different spatial-frequency components of an illuminated object correspond to optical plane waves propagating from the object along different directions. Importantly, with this approach the filter transfer function can be tailored through the design of the metasurface, and different metasurfaces can be fabricated on different adjacent pixels within the same image sensor array. As a result, multiple filtering operations can be performed simultaneously on the same object with the same sensor array. Moreover, this approach does not require any external optical components other than an imaging lens, and thus can provide particularly small form factors and simple alignment.

To illustrate the unique capabilities of these devices, we consider the specific task of edge detection under spatially incoherent (i.e., ambient) illumination. It is well established that the incoherent frequency response of an optical spatial filter is governed by its optical transfer function (OTF) $T(\mathbf{q}) = I_{out}(\mathbf{q})/I_{in}(\mathbf{q})$, which is given by the autocorrelation of the coherent transfer function and thus is always maximum for zero in-plane wavevector $\mathbf{q}$ [3]. As a result, incoherent edge detection by high-pass filtering is generally impossible with a single optical spatial filter. A possible solution is to record two low-pass-filtered images of the same object with different cutoff frequencies and then compute their difference, which however typically requires exceedingly bulky setups or complicated multiplexing schemes [4]. Instead, here we investigate the use of a camera where a (low-pass filtering) angle-sensitive metasurface is fabricated on every other pixel in a checkerboard pattern, while all other devices are left uncoated. The difference between the two images collected by the coated and bare pixels therefore only contains the high-$\mathbf{q}$ frequency components of the object. The resulting images are evaluated computationally based on the experimental angular response of prototype devices, showing clear edge enhancement with high contrast.

2. Results and discussion

The principle of operation of our directional image sensors is illustrated in Fig. 1(a). The illumination window of a photodetector is coated with a composite metasurface consisting of a metal film stacked with a periodic array of rectangular metallic nanoparticles (NPs) and perforated with suitably positioned sub-wavelength slits. Light arriving at the desired detection angle (in this case normal incidence) is diffracted by the NPs into surface plasmon polaritons (SPPs) on the metal film, which are then scattered by the slits into radiation propagating predominantly into the absorbing active layer. Light incident along any other direction is instead either reflected or diffracted back. The experimental devices are based on Ge photoconductors, with the metasurfaces designed for operation at 1550 nm and fabricated using standard lithographic techniques [Fig. 1(b)]. Angle-resolved photocurrent measurements show highly directional response [Fig. 1(c)], in good agreement with theoretical expectations. In passing it should be noted that, while the present devices are wavelength selective and thus require spectral filtering, achromatic broadband operation is also possible with more complex gradient metasurfaces based on similar NPs.

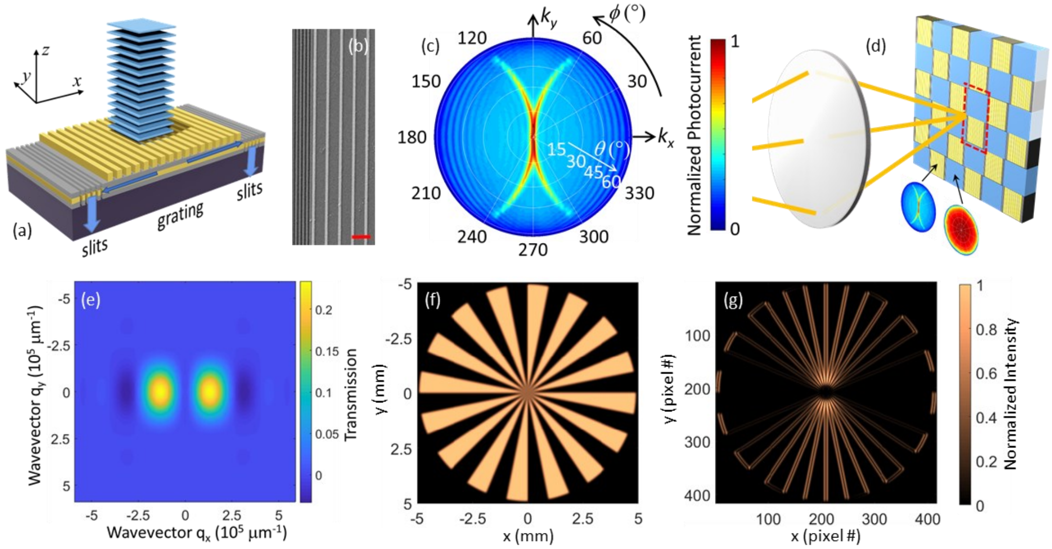

Fig. 1. (a) Schematic illustration of a plasmonic directional photodetector. (b) Top-view SEM image of a device showing the slits and a few adjacent NPs. The scale bar is 2 µm. (c) Measured photocurrent vs polar and azimuthal angles of incidence at 1550 nm. (d) Schematic illustration of the pixel arrangement for incoherent edge detection. (e) Effective OTF $\Delta T(\mathbf{q})$ of the resulting imaging system, computed from the difference of the OTFs of uncoated and plasmonic pixels. (f), (g) Representative object (f) and edge-enhanced image (g).

To evaluate the image processing capabilities of these devices, we have developed a theoretical model for their spatial frequency response. The key conclusion of this analysis is that these devices essentially sample the incident field distribution at the slit locations, according to a (discrete-space) coherent transfer function determined by their angle-dependent responsivity. Based on this notion, we could then compute their OTF from the measured responsivity data of Fig. 1(c) using standard formulas from Fourier optics and sampling theory, including the effects of the finite pixel size and of the imaging lens. The same procedure was also applied to the uncoated pixels of the envisioned camera [Fig. 1(d)], whose responsivity is essentially constant with angle of incidence. In Fig. 1(e) we plot the difference $\Delta T(\mathbf{q})$ between the OTFs of these two types of devices (each normalized to unit peak value). The resulting frequency response function vanishes at $\mathbf{q} = 0$ and increases nearly quadratically with q_x over a sufficiently broad portion of the accessible spatial-frequency range. This pixel configuration can therefore provide second-order differentiation (along the x direction), which is the standard mathematical operation used for edge detection.

Figs. 1(f) and 1(g) show a representative object (a spoke pattern) and its recorded image from the camera of Fig. 1(d), computed using the OTF $\Delta T(\mathbf{q})$ of Fig 1(e). Clear edge enhancement is observed, with two peaks per edge due to the second-order-derivative nature of the underlying filter. Consistent with the anisotropic shape of $\Delta T(\mathbf{q})$, maximum contrast (with peak-to-average-background ratio > 1000) is obtained for the edges oriented along the y direction (i.e., the direction of the NPs in the plasmonic image sensors), whereas x-oriented edges are not resolved. This ability to visualize different features of an object depending on their orientation is especially attractive for use in pattern recognition, in conjunction with additional data processing with a CNN. Importantly, power budget considerations also indicate that the computational cost of producing these images (only associated with the subtraction steps) can be a factor of about 10 smaller than fully electronic solutions for similar filtering operations. Combined with the lack of external optical elements, as in traditional Fourier-optics spatial filters, this property makes the envisioned cameras particularly promising for image processing applications in portable devices.

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3. References

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