Polarization-selective optical transmission through a plasmonic metasurface

Charles Pelzman and Sang-Yeon Cho^{a)}

Klipsch School of Electrical and Computer Engineering, New Mexico State University, Las Cruces, New Mexico, 88003-8001, USA

(Received 7 March 2015; accepted 15 June 2015; published online 22 June 2015)

We present the design, fabrication, and experimental characterization of a nanoslit-based metasurface that offers polarization-selective optical transmission for advanced imaging applications. The metasurface consists of an array of meta-atoms, constructed with two orthogonally coupled subwavelength apertures. Highly enhanced optical transmission was achieved by selective excitation of surface plasmon waves on the metasurface. By rotating the orientation of the linearly polarized incident beam, switching of enhanced optical transmission bands through the metasurface was experimentally demonstrated. This demonstration is a significant step towards developing advanced multispectral imaging devices. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4922993>]

The performance of conventional optical devices is fundamentally limited by the optical properties of materials available in nature. Artificial photonic materials, such as metamaterials, have attracted considerable attention due to their ability to control fundamental electromagnetic properties: permittivity ϵ and permeability μ . Optical metasurfaces are broadly defined as two-dimensional metamaterials constructed with a periodic or a random arrangement of subwavelength building blocks, meta-atoms.¹ The optical properties of metasurfaces can be precisely tailored through the engineered interaction of meta-atoms with light. Recently, several unusual optical phenomena, such as anomalous reflection and refraction,^{2,3} generation of optical orbital angular momentum,⁴ aberration-free imaging,⁵ and artificial birefringence^{6,7} have been demonstrated using plasmonic antenna-based metasurfaces.

Subwavelength metallic structures are commonly used as meta-atoms because of their strong interaction with light. Highly enhanced optical transmission, known as extraordinary optical transmission (EOT),^{8,9} through single and multiple subwavelength metallic apertures has been observed. After the initial demonstration of EOT through an array of circular nanometer scale holes,⁸ subwavelength metallic structures with different geometries, such as rectangular,¹⁰ cross,¹¹ L-shape,¹² and V-shape,² have been investigated. These studies showed that the geometrical symmetry of the subwavelength apertures plays a key role in determining the polarization dependence of the structure's optical properties.

In this paper, we present the design, fabrication, and experimental characterization of a nanoslit-based metasurface that offers polarization-selective optical transmission for hyperspectral imaging applications. The demonstrated metasurface consists of an array of meta-atoms, created by patterning subwavelength rectangular apertures with focused-ion-beam (FIB) milling in a thin metal film. The nanoslit-based metasurface supports multiple EOT peaks that can be individually selected by changing the polarization direction of incident light. When the orientation of a linearly polarized incident beam is aligned perpendicular to the long

axis of one of the rectangular apertures, the metasurface allows highly enhanced optical transmission through excitation of a surface plasmon wave at a designed spectral band. The demonstrated nanoslit-based metasurface offers great potential for polarization-selective multispectral imaging applications since it can be directly mounted on a conventional image sensor, such as a charge-coupled-device (CCD) camera. A low-cost, high-throughput nanolithography technique, such as nanoimprint lithography, can be used for mass production of the demonstrated metasurface.

The nanoslit-based metasurface is a two-dimensional array of coupled subwavelength apertures. Figure 1 presents a schematic of the nanoslit-based metasurface. The meta-atom can be created by patterning two coupled subwavelength rectangular apertures in a metal film. When a linearly polarized input beam is aligned perpendicular to the long axis of one of the apertures, the incident photons gain additional momentum from the periodicity of the meta-atoms, exciting surface plasmon waves. The excitation efficiency can be greatly enhanced when the wavelength of the incident beam is matched to one of the resonance wavelengths of the surface plasmon waves. The resonance wavelength of the metasurface is derived from the phase-matching condition⁸

FIG. 1. Schematic of the nanoslit-based metasurface. Polarization-selective optical transmission is achieved through excitation of surface plasmon polaritons by orthogonally coupled subwavelength rectangular apertures. The inset presents the unit cell structure of the metasurface.

^{a)}Electronic mail: sangyeoncho@nmsu.edu

$$\lambda_{(i,j)} = \frac{\Lambda_x \Lambda_y}{\sqrt{((i\Lambda_y)^2 + (j\Lambda_x)^2)}} \sqrt{\frac{(\epsilon_1 \epsilon_2)}{(\epsilon_1 + \epsilon_2)}}, \quad (1)$$

where Λ_x and Λ_y are the lattice constants of the metasurface, i and j are integers, and ϵ_1 and ϵ_2 are the permittivity values of metal and the surrounding medium, respectively. The enhanced optical transmission of the metasurface is due to the re-radiation of the excited surface plasmon waves through the interaction with meta-atoms.

The resonance wavelengths of the metasurface are determined by the lattice constant parallel to the orientation of the input polarization. For example, the resonance wavelength of the metasurface for a y-polarized input is determined by Λ_y . Using Eq. (1), the calculated resonance wavelengths of the first-order modes for x-polarized and y-polarized excitations with $\Lambda_x = 450$ nm and $\Lambda_y = 350$ nm are around $\lambda_{(1,0)} = 720$ nm and $\lambda_{(0,1)} = 600$ nm, respectively. Based on the calculated resonant wavelengths, an array of the meta-atoms was patterned on a 100-nm thick Au film using FIB. For fabrication, a glass substrate was thoroughly cleaned using acetone, methanol, and isopropanol. After drying the substrate on a hot plate at 120 °C for 30 min, a 5 nm Ti and a 100 nm Au layers were deposited using an electron-beam evaporator. The rectangular apertures were patterned using FIB at 30 kV with a beam current of 100 pA.

The fabricated metasurface was inspected and characterized using a scanning electron beam microscope (SEM). The measured dimensions of the slits were around 250 nm by 60 nm and 190 nm by 60 nm with a variation of ± 20 nm. The observed variation is due to the finite spot size and the beam drift of the FIB system. Figure 2 shows an SEM image of the fabricated metasurface.

The transmission spectra of the metasurface were calculated using a finite-element-method (FEM) solver, *COMSOL Multiphysics*TM. The inset in Figure 3 depicts a schematic drawing of the meta-atom. A linearly polarized plane wave was used as an excitation for the simulation. Periodically

FIG. 2. Scanning electron beam microscope image of the fabricated metasurface using a focused-ion-beam milling system. The measured overall size of the individual meta-atom was 460 nm $\times$ 360 nm.

FIG. 3. Calculated transmittance of the metasurface versus free-space wavelength for x- and y-polarized inputs. The lattice constants of the meta-atom were varied from 460 nm to 500 nm and 360 nm to 400 nm along x and y directions, respectively. Switching of EOT peaks for different input polarization was confirmed. The insets present the calculated distribution of the electric field in the meta-atom, showing selective excitation of the surface plasmon waves.

coupled meta-atoms with two orthogonally coupled slits with the same dimensions of the fabricated sample were defined using periodic boundary conditions along the x and y axes. In the simulation, the complex dielectric function of Au was obtained using the experimental values from Johnson and Christy.¹³ The computational domain was terminated with two perfectly matched layers to prevent any undesired reflections from the boundaries.

The calculated transmission spectra of the metasurface show polarization-selective switching of EOT. The transmittance spectra of the metasurface with different lattice constants were calculated, showing the scalability of the switching operation. As shown in Figure 3, the center wavelength of EOT around 600 nm for a y-polarized input was switched to 700 nm by rotating the polarization direction of the input beam 90°, i.e., x-polarized.

The spectral response of the fabricated metasurface was measured using a customized transmission microscope setup.

FIG. 4. Experimental setup used to measure the transmitted spectrum of the metasurface. QTH represents a quartz-tungsten-halogen, POL represents a birefringence polarizer, BS represents a beam splitter, NDF represents a variable neutral density filter, MS represents a metasurface, and FSP represents a fiber-coupled spectrometer.

FIG. 5. Measured transmittance spectra of the fabricated metasurface for x- and y-polarized inputs, showing polarization-selective switching of EOT bands. The inset shows an SEM image of the fabricated meta-atom with the measured polarization directions.

Figure 4 presents a schematic of the measurement setup. A quartz-tungsten-halogen (QTH) lamp coupled with a birefringence polarizer was used to illuminate the sample with a linearly polarized broadband beam. The birefringence polarizer was mounted on a rotation stage to control the polarization direction of the input beam. The birefringence polarizer was chosen because of its high extinction ratio (100 000:1). A high numerical aperture microscope objective was used to focus the input beam on the metasurface. The transmitted optical beam was collected and analyzed using a fiber-coupled CCD spectrometer (CCS 175 from Thorlabs). To avoid undesired saturation of the measured signal by the spectrometer, a variable neutral density filter (NDF) was inserted.

The measurement procedure of the metasurface is as follows: The transmission spectra $I_{\text{META}}(\lambda)$ of the metasurface for different polarization angles were measured at a fixed exposure time, τ of the CCD spectrometer. After removing the metasurface sample, the emission of the QTH source was collected by the spectrometer. Due to the limited dynamic range of the spectrometer, a NDF was inserted in the excitation path of the measurement setup. By adjusting the optical density (OD) of the NDF, the peak intensity value of the emission spectrum $I_{\text{QTH}}(\lambda)$ of the QTH source was matched to the peak value of $I_{\text{META}}(\lambda)$ at the same exposure time, τ . The transmittance spectra of the metasurface were calculated by $I_{\text{META}}(\lambda)/(I_{\text{QTH}}(\lambda)10^{\text{OD}})$. Figure 5 shows the measured transmittance spectra of the fabricated metasurface. Highly enhanced optical transmission through the metasurface was observed around 625 nm for a y-polarized input. After rotating the birefringence polarizer 90° , the transmission band was switched to 710 nm. The change in the resonance wavelength is due to selective excitation of surface plasmon waves on the metasurface. As the polarization direction of the incident electric field is rotated from the y-axis to the x-axis, the horizontally oriented apertures in the metasurface contribute less to the overall transmission and the contribution from the vertically oriented apertures becomes dominant. The measured peak transmittance of the metasurface is around 0.1, which is within the range of reported peak

transmission values of experimentally demonstrated EOT based devices in the literature.⁸ For imaging applications, the transmitted signal of the metasurface can be further amplified through the use of electronic circuits. Discrepancies between the calculated and the measured transmission spectra, presented in Figures 3 and 5, can be caused by the variation of the physical dimension of the fabricated meta-atoms.

We present the design, fabrication, and experimental demonstration of a nanoslit-based metasurface. The demonstrated metasurface utilizes polarization-selective excitation of surface plasmon waves in orthogonally coupled subwavelength apertures. Selective excitation of EOT in the fabricated metasurface was experimentally demonstrated and confirmed through numerical modeling. The demonstrated metasurface can be used to create polarization-selective optical devices for multispectral imaging applications.

This material is based upon work supported by, or in part by, the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF-12-1-0050, 60492-EL-REP. This work was supported by the National Institutes of Health under Grant No. 1R01ES021951-01 and the National Science Foundation under Grant No. 1311735. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-AC04-94AL85000).

- ¹A. V. Kildishev, A. Boltasseva, and V. M. Shalae, *Science* **339**(6125), 1232009 (2013); F. Aieta, P. Genevet, M. Kats, and F. Capasso, *Opt. Express* **21**(25), 31530 (2013).
- ²N. Yu and F. Capasso, *Nat. Mater.* **13**(2), 139 (2014).
- ³N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, *Science* **334**(6054), 333 (2011); S. Sun, K.-Y. Yang, C.-M. Wang, T.-K. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W.-T. Kung, and G.-Y. Guo, *Nano Lett.* **12**(12), 6223 (2012).
- ⁴E. Karimi, S. A. Schulz, I. De Leon, H. Qassim, J. Upham, and R. W. Boyd, *Light: Sci. Appl.* **3**(5), e167 (2014).
- ⁵F. Aieta, P. Genevet, M. A. Kats, N. Yu, R. Blanchard, Z. Gaburro, and F. Capasso, *Nano Lett.* **12**(9), 4932 (2012).
- ⁶B. Frank, X. Yin, M. Schäferling, J. Zhao, S. M. Hein, P. V. Braun, and H. Giessen, *ACS Nano* **7**(7), 6321 (2013).
- ⁷Y. Zhao and A. Alù, *Nano Lett.* **13**(3), 1086 (2013).
- ⁸T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, *Nature* **391**(6668), 667 (1998).
- ⁹A. Degiron, H. J. Lezec, N. Yamamoto, and T. W. Ebbesen, *Opt. Commun.* **239**(1), 61 (2004); R. Gordon, A. G. Brolo, A. McKinnon, A. Rajora, B. Leathem, and K. L. Kavanagh, *Phys. Rev. Lett.* **92**(3), 037401 (2004).
- ¹⁰K. J. Klein Koerkamp, S. Enoch, F. B. Segerink, N. F. Van Hulst, and L. Kuipers, *Phys. Rev. Lett.* **92**(18), 183901 (2004).
- ¹¹C.-Y. Chen, M.-W. Tsai, T.-H. Chuang, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **91**(6), 063108 (2007).
- ¹²T. Li, H. Liu, S.-M. Wang, X.-G. Yin, F.-M. Wang, S.-N. Zhu, and X. Zhang, *Appl. Phys. Lett.* **93**(2), 021110 (2008).
- ¹³P. B. Johnson and R.-W. Christy, *Phys. Rev. B* **6**(12), 4370 (1972).