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14. ABSTRACT

We have 1) experimentally demonstrated a plasmon-assisted multispectral and polarization selective imaging device and 2) developed a complex refractive index estimation algorithm based on a polarized microfacet bidirectional reflectance distribution function (pBRDF) model, and 3) developed a metasurface surface that can extract the Stokes parameters directly from a focal plane array for advanced imaging applications.
From this project, we published 7 peer-reviewed journal papers and 6 conference papers in internal conferences.
Currently, 2 journal papers are under review. Two PhDs and two students with their MS degree have been produced

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Report Title

Final Report: Development of Plasmon-assisted Quantum Dot Sensors for Multispectral and Polarization Selective Imaging

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/22/2017	7	Charles Pelzman: Sang-Yeon Cho. Polarization-selective optical transmission through a plasmonic metasurface, Applied Physics Letters, (06 2015): . doi: 10.1063/1.4922993
02/22/2017	11	Hanyu Zhan, David G. Voelz. Modified polarimetric bidirectional reflectance distribution function with diffuse scattering: surface parameter estimation, Optical Engineering, ( ): 123103. doi:
02/22/2017	10	Hanyu Zhan: David G. Voelz: Sang-Yeon Cho: Xifeng Xiao. Complex index of refraction estimation from degree of polarization with diffuse scattering consideration, Applied Optics, ( ): 9889. doi:
02/22/2017	12	Charles Pelzman, Sang-Yeon Cho. Plasmonic metasurface for simultaneous detection of polarization and spectrum, Optics Letters, ( ): 1213. doi:
02/22/2017	13	Jayson Briscoe, Sang-Yeon Cho. Hybridised extraordinary optical transmission in plasmonic cavity, Electronics Letters, ( ): 1860. doi:
02/22/2017	14	Jayson L. Briscoe, Sang-Yeon Cho, Igal Brener. Part-Per-Trillion Level Detection of Microcystin-LR Using a Periodic Nanostructure, IEEE Sensors Journal, ( ): 1366. doi:
TOTAL:		**6**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
02/22/2017	15	Charlez Pelzman, Sang-Yeon Cho. A plasmonic subwavelength aperture array for polarimetric and multispectral imaging, 2015 IEEE Photonics Conference (IPC). 04-OCT-15, Reston, VA. : ,
02/22/2017	16	Charles Pelzman, Sang-Yeon Cho. Polarization-selective switching of extraordinary optical transmission though a metasurface, 2015 IEEE Photonics Conference (IPC). 04-OCT-15, Reston, VA. : ,
02/22/2017	17	Hanyu Zhan ; David G. Voelz ; Xifeng Xiao ; Sang-Yeon Cho. Polarization-based complex index of refraction estimation with diffuse scattering consideration, SPIE Optical Engineering + Applications. 01-SEP-15, San Diego, California, United States. : ,
02/22/2017	18	Hanyo Zhan, David G. Voelz, Sang-Yeon Cho. Index of refraction estimation from Stokes parameters with diffuse scattering consideration, SPIE Commercial + Scientific Sensing and Imaging. 04-MAY-16, Baltimore, Maryland, United States. : ,

TOTAL: **4**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
02/22/2017	4.00	Jayson Briscoe, Sang-Yeon Cho, Igal Brener. Defect-Assisted Plasmonic Sensing, IEEE Sensors Conference. 04-NOV-13, Baltimore, USA. : ,
02/22/2017	8.00	Sang-Yeon Cho, Jayson Briscoe. Enhanced sensitivity in periodically coupled antenna sensors, 2014 IEEE Sensors. 02-NOV-14, Valencia, Spain. : ,
02/22/2017	9.00	Jayson Briscoe, Sang-Yeon Cho. Low level detection of microcystin using a plasmonic biosensor, 2014 IEEE Sensors. 02-NOV-14, Valencia, Spain. : ,
TOTAL:		**3**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Charles Pelzman	0.50	
Hanyu Zhan	0.25	
FTE Equivalent:	**0.75**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Sang-Yeon Cho	0.17	
David Voelz	0.08	
FTE Equivalent:	**0.25**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	2.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	2.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME	
Nadeepa Jayasundara	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Jayson Briscoe	
Hanyu Zhan	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Development of Plasmon-assisted Quantum Dot Sensors for Multispectral and Polarization Selective Imaging

Investigators: Sang-Yeon Cho and David Voelz, Klipsch School of Electrical and Computer Engineering, New Mexico State University, Las Cruces, NM 88003.

ABSTRACT

We have 1) experimentally demonstrated a plasmon-assisted multispectral and polarization selective imaging device and 2) developed a complex refractive index estimation algorithm based on a polarized microfacet bidirectional reflectance distribution function (pBRDF) model, and 3) developed a metasurface surface that can extract the Stokes parameters directly from a focal plane array for advanced imaging applications.

From this project, we published 7 peer-reviewed journal papers and 7 conference papers in internal conferences. Currently, 2 journal papers are under review. Two PhDs and two students with their MS degree have been produced by this grant. Currently, one student who was supported by this grant is pursuing his PhD at New Mexico State University.

1. STATEMENT OF THE PROBLEM STUDIED

In this project, we are investigating new electro-optic (EO) sensors that can provide pixel-level multispectral and polarimetric sensing. The specific objectives of the proposed research include 1) investigation of absorption enhancement by the interaction between surface plasmon polaritons (SPPs) and quantum dots in QD PDs, 2) utilization of the extraordinary optical properties of a plasmonic antenna, 3) advanced bandgap engineering of a QD PD via quantum size effects, 4) enhanced quantum efficiency through surface customization of QDs, and 5) development of device characterization setups for high-speed measurement and dispersion characterization. Findings of this research project will contribute significantly toward the understanding of the role of SPPs in the generation and transport of optically generated carriers in nanoscale QD PDs for advanced optical imaging applications such as remote sensing. We are also studying application aspects of these EO sensors for problems of interest to the DoD.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

We have demonstrated novel metasurface-based imaging devices that can provide polarization and wavelength selective imaging capabilities. In addition, we have applied the plasmonic nanostructure for other sensing applications. A complex refractive index estimation algorithm has been developed by the PIs. Below shows a list of published and submitted papers, supported by this research grant.

Peer-Reviewed Journal Papers

1. H. Zhan, D. G. Voelz, H. Jiang, M. Kupinski, “Parameter-based images generated from polarimetric measurements for remote target analysis,” Opt. Lett. (2017), Under Review.
2. Charles Pelzman and Sang-Yeon Cho, "Control of Plasmon Resonance by Mode Coupling in Metal-Dielectric Nanostructures," AIP Journal of Applied Physics (2017), Under Review.
3. Charles Pelzman and Sang-Yeon Cho, "Plasmonic Metasurface for Simultaneous Detection of Polarization and Spectrum," OSA Optics Letters 41, 1213-1216, 2016.
4. H. Zhan, D. G. Voelz, “Modified polarimetric bidirectional reflectance distribution function with diffuse scattering: surface parameter estimation.” Opt. Eng., 55(12), 123103–123103 (2016).
5. Hanyu Zhan, David G. Voelz, Sang-Yeon Cho, Xifeng Xiao, "Complex index of refraction estimation from degree of polarization with diffuse scattering consideration," OSA Applied Optics 54, 9889-9895 (2015).
6. Charles Pelzman and Sang-Yeon Cho, “Polarization-selective optical transmission through a plasmonic metasurface,” AIP Applied Physics Letters 106, 251101 (2015).
7. Jayson L. Briscoe and Sang-Yeon Cho, “Part-Per-Trillion Level Detection of Microcystin-LR using a Periodic Nanostructure,” IEEE Sensors Journal 14, 1399-1404 (2015).
8. Jayson L. Briscoe and Sang-Yeon Cho, “Hybridized Extraordinary Optical Transmission in a Plasmonic Cavity,” IEE Electronics Letters 50, 1860-1862 (2014).
9. Jayson L. Briscoe, Nadeepa Jayasundara, and Sang-Yeon Cho, “Surface-Plasmon-Polariton Assisted Modification of Spontaneous Emission of Colloidal Quantum Dots in Metal Nanostructures,” *Applied Physics Letters*, 104303, 2013; doi: 10.1063/1.4776736.

Conference Papers

1. H. Zhan, D. G. Voelz, S.-Y. Cho, “Index of refraction estimation from Stokes parameters with diffuse scattering consideration,” Proc. SPIE 9853, Polarization: Measurement, Analysis, and Remote Sensing XII, 985304 (May 4, 2016); doi:10.1117/12.2223951.
2. Hanyu Zhan, David G. Voelz, Xifeng Xiao, Sang-Yeon Cho, “Polarization-based complex index of refraction estimation with diffuse scattering consideration,” SPIE Proc. 9613, paper 9613-33 (2015).
3. Charles Pelzman and Sang-Yeon Cho, "A Plasmonic Subwavelength Aperture Array for Polarimetric and Multispectral Imaging," The 2015 IEEE Photonics Conference, 28th Annual Conference of the IEEE Photonics Society (IPC), WA3.5, 2015.
4. Charles Pelzman and Sang-Yeon Cho, "Polarization-Selective Switching of Extraordinary Optical Transmission Through a Metasurface", The 2015 IEEE Photonics Conference, 28th Annual Conference of the IEEE Photonics Society (IPC), WH3.3, 2015.

5. Jayson L. Briscoe and Sang-Yeon Cho, “Low Level Detection of Microcystin Using a Plasmonic Biosensor,” IEEE Sensors Conference, 2-5 November 2014, pp. 313-316.
6. Sang-Yeon Cho and Jayson L. Briscoe, “Enhanced Sensitivity in Periodically Coupled Antenna Sensors,” IEEE Sensors Conference, 2-5 November 2014, pp. 1897-1899.
7. Jayson L. Briscoe, Sang-Yeon Cho, and Igal Brener, "Defect-assisted Plasmonic Sensing," IEEE Sensors Conference, Baltimore MD, Paper: 7560, 2013.

Ph. D. Thesis

1. “Surface plasmon polaritons in artificial metallic nanostructures / by Jayson Lawrence Briscoe,” Ph.D. Thesis, New Mexico State University, May 2015.
2. “Polarization-based refractive index and surface roughness estimation with diffuse scattering consideration for remote sensing applications / by Hanyu Zhan,” Ph.D. Thesis, New Mexico State University, May 2016.

2-1. DEMONSTRATION OF POLARIZATION-SELECTIVE OPTICAL TRANSMISSION THROUGH A PLASMONIC METASURFACE

We have developed 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 condition:

$$\lambda_{(i,j)} = \frac{\Lambda_x \Lambda_y}{\sqrt{\left((i\Lambda_y)^2 + (j\Lambda_x)^2\right)}} \sqrt{\frac{(\varepsilon_1 \varepsilon_2)}{(\varepsilon_1 + \varepsilon_2)}}, \tag{1}$$

where Λx and Λy are the lattice constants of the metasurface, i and j are integers, $\varepsilon 1$ and $\varepsilon 2$ 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.

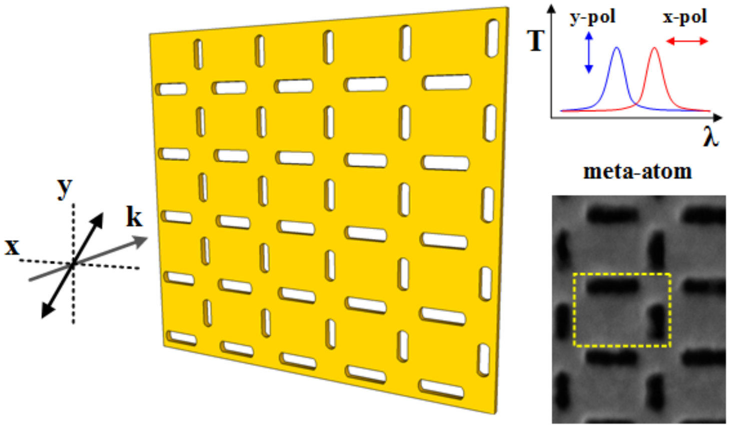

Fig. 1. Schematic of the nanoslit-based metasurface. Polarization-selective optical transmission is achieved through excitation of surface plasmon polaritons by orthogonally coupled subwavelength rectangular apertures. The inset presents the unit cell structure of the metasurface.

The transmission spectra of the metasurface were calculated using a finite-element-method solver, COMSOL Multiphysics$^{\text{TM}}$. The inset in Figure 2 depicts a schematic drawing of the meta-atom. A linearly polarized plane wave was used as an excitation for the simulation. Periodically 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. The computational domain was terminated with two perfectly matched layers to prevent any undesired reflections from the boundaries.

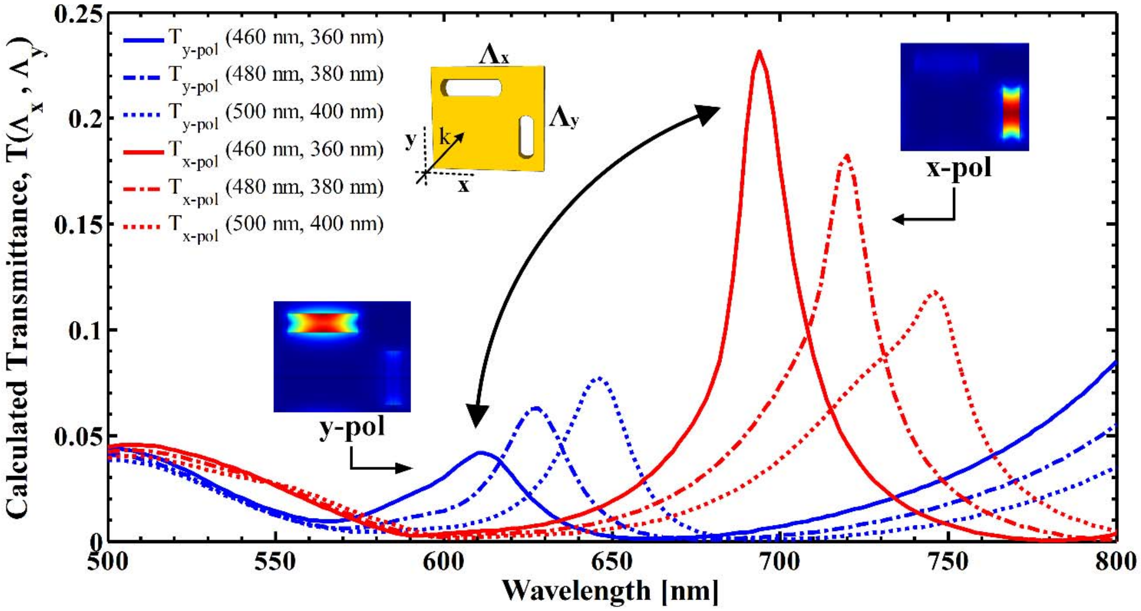

Fig. 2. Calculated transmittance of the metasurface versus free-space wavelength for x- and y-polarized inputs. The lattice constants of the meta-atom were varied from 460 nm to 500 nm and 360 nm to 400 nm along x and y directions, respectively. Switching of EOT peaks for different input polarization was confirmed. The insets present the calculated distribution of the electric field in the meta-atom, showing selective excitation of the surface plasmon waves.

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 2, 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 90º, i.e. x-polarized.

The spectral response of the fabricated metasurface was measured using a customized transmission microscope setup. Figure 2 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. 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.

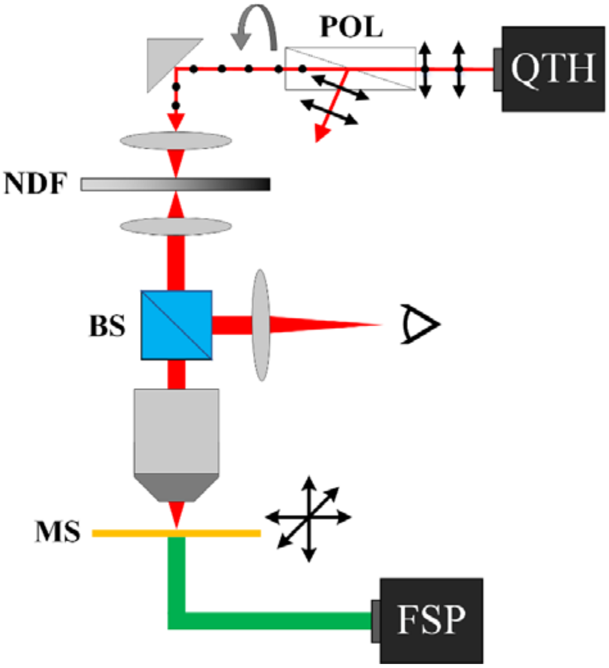

Fig. 3. Experimental setup used to measure the transmitted spectrum of the metasurface. QTH represents a quartz-tungsten-halogen, POL represents a birefringence polarizer, BS represents a beam splitter, NDF represents a variable neutral density filter, MS represents a metasurface, and FSP represents a fiber-coupled spectrometer.

The measurement procedure of the metasurface is as follows: The transmission spectra IMETA (λ) 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 IQTH (λ) of the QTH source was matched to the peak value of IMETA (λ) at the same exposure time, τ. The transmittance spectra of the metasurface were calculated by IMETA(λ)/(IQTH(λ)10OD).

Figure 4 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. For imaging applications, the transmitted signal of the metasurface can be further amplified through the use of electronic circuits.

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.

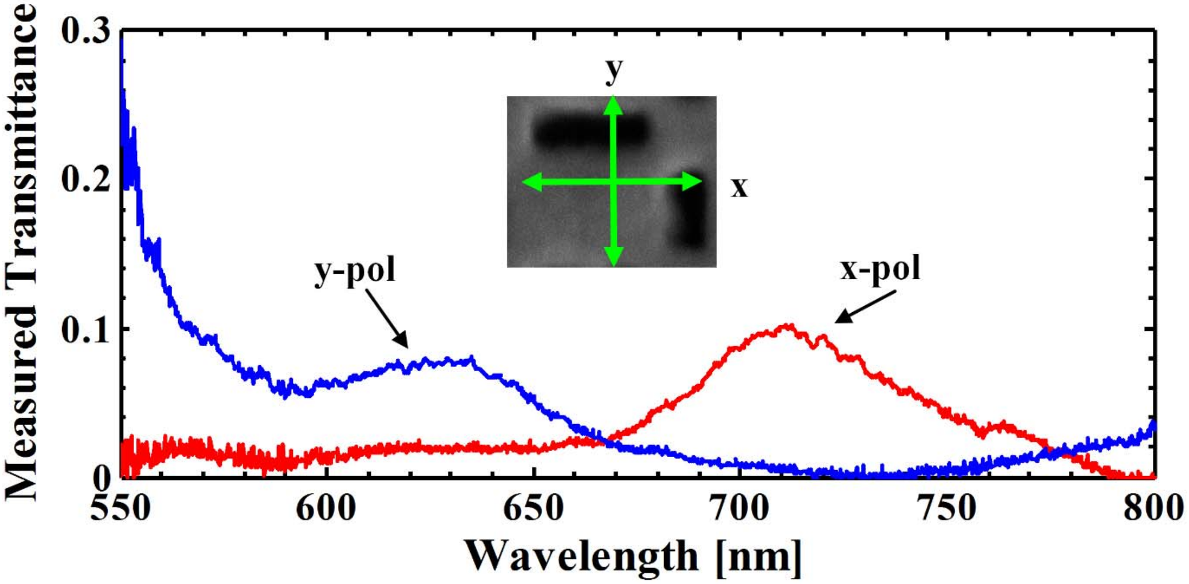

Fig. 4 Measured transmittance spectra of the fabricated metasurface for x- and y-polarized inputs, showing polarization-selective switching of EOT bands. The inset shows an SEM image of the fabricated meta-atom with the measured polarization directions.

Simultaneous Detection of Polarization and Spectrum using a Plasmonic Metasurface

we present a new plasmonic metasurface that allows simultaneous detection of polarization and spectral information of incident light. A rationally designed cluster of different artificial atoms exhibits polarization and wavelength selective optical transmission via excitation of surface plasmon (SP) waves. Each group of meta-atoms strongly interacts with a linearly polarized input with a specific angle of polarization (AoP) within a target spectral band. This engineered interaction of light with the meta-atom arrays leads to polarization-selective resonant optical tunneling. The demonstrated plasmonic metasurface has potential to revolutionize existing multispectral and polarimetric optical systems by offering simultaneous spectral and polarization detection capabilities.

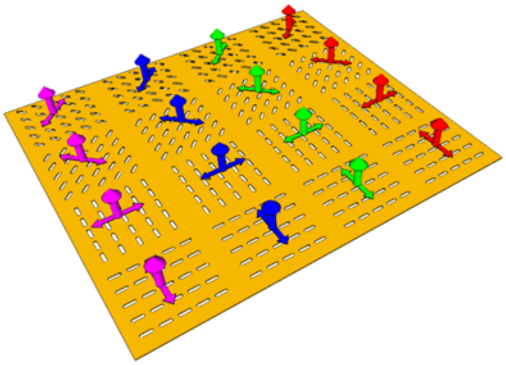

Fig. 5. Schematic diagram of the plasmonic metasurface, showing spatially filtered spectral and polarization components in the transmitted signal.

The optical transmission of the plasmonic metasurface was measured using a tunable broadband source and a customized confocal setup. A quartz-tungsten-halogen (QTH) lamp coupled with a VIS-NIR monochromator was used as the tunable light source. The output beam from the monochromator was partially linearly polarized. To effectively control the polarization angle of the input, a quarter wave plate was used to convert from linear to circular polarization. The circular polarized light was then used as an input to the second linear polarizer to select the input polarization angle. This will ensure same intensity while changing the AoP of the input. The linearly polarized light from the second polarizer was used to illuminate the metasurface. A high numerical aperture microscope objective was used to collect the transmitted light from the metasurface. The collected beam was then focused onto a monochromatic CMOS camera to analyze the intensity distribution.

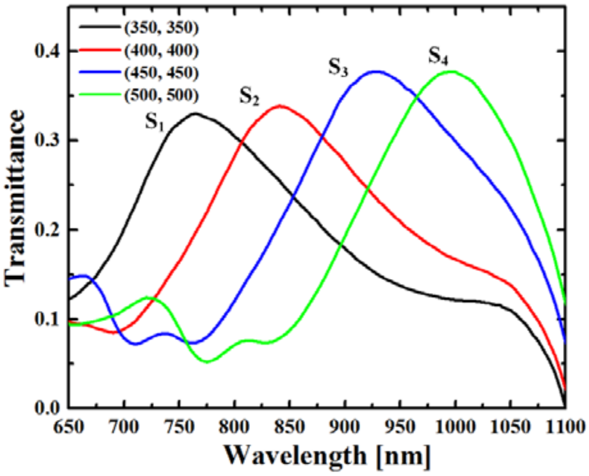

Fig. 6. Measured transmission spectra of individual meta-atom arrays of different lattice constants, showing four highly tunable transmission bands.

Polarimetric imaging systems utilize angle of polarization (AoP) to determine the polarization of an object taken from the image. The AoP methodology measures the intensity difference between 0, 90, 45 and 135 degrees:

$$AoP = \frac{1}{2}\arctan\left(\frac{\left(\sum_{m=L3+1}^{L4}\sum_{n=0}^{H1}\left(P_1(m,n)\right)\right)-\left(\sum_{m=L2+1}^{L3}\sum_{n=0}^{H1}\left(P_2(m,n)\right)\right)}{\left(\sum_{m=L0}^{L1}\sum_{n=0}^{H1}\left(P_4(m,n)\right)\right)-\left(\sum_{m=L1+1}^{L2}\sum_{n=0}^{H1}\left(P_3(m,n)\right)\right)}\right)$$

Using the AoP equation the incident polarization is determined for each wavelength in the sensor, which can be designed to contain a large spectral band based on periodic grating of the nanoslits. The fabricated structure was patterned on 100nm thick Au film on a glass substrate. The rectangular nanoslits were milled using a focused ion beam to form a super cell containing 15umx15um subcells consisting of 350nm, 400nm, 450nm and 500nm period nanoslits, with slit lengths 175nm, 200nm, 225nm, 250nm and 70nm width.

To measure the spectral response of the spatially distributed meta-atoms, a linearly polarized input was focused onto a column of the metasurface. Each column was sequentially illuminated by moving the metasurface using a translation stage. The transmitted light from the illuminated column of the metasurface was collected through the microscope objective. Figure 6 shows the measured spectral responses of individual columns in the metasurface, showing four highly tunable transmission bands.

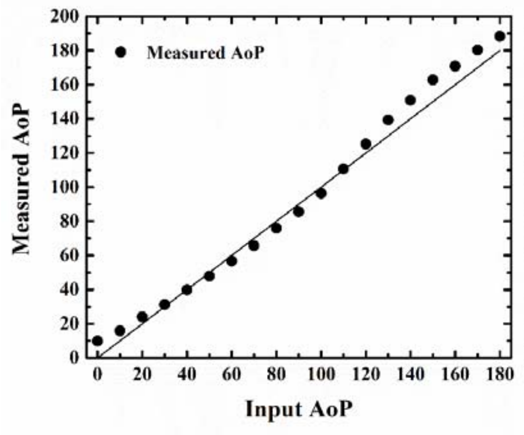

Fig. 7. Measured AoP from the transmitted signal through the fabricated metasurface.

Figure 7 shows the measured polarization response of the metasurface. For this measurement, the metasurface was illuminated with an optical input, centered at λ = 760 nm.

2-2. POLARIZATION-BASED COMPLEX INDEX OF REFRACTION ESTIMATION

The sensor technologies under development in this program can be applied to a variety of applications of interest to the DoD, such as remote sensing, detection and imaging. A part of our work involves the consideration of some fundamental sensing processes that will incorporate the new sensors. The complex index of refraction is a fundamental parameter for the discrimination or classification of materials and polarization sensing provides an approach for obtaining an estimate of the index of refraction. Our work on this subject involves the study of a polarimetric refractive index estimation approach in the presence of an unknown, unpolarized diffuse component in the polarimeter measurements. The unpolarized light, whether from the surface scatter itself or some inconsistencies in the polarization sensing element, can bias the index of refraction estimate.

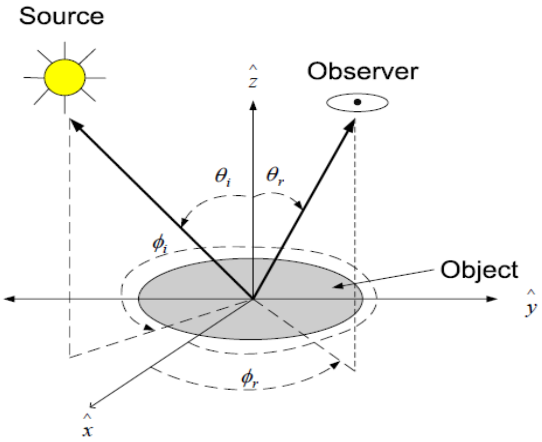

Fig. 8. Geometry for polarimetric measurement and estimate of index of refraction

During this period we developed a computer simulation based on a polarized microfacet bidirectional reflectance distribution function (pBRDF) model. Multiple passive polarization measurements or images of a surface are collected (simulated) for several geometries and a model-based recovery using a nonlinear Levenberg-Marquardt algorithm is used to obtain a complex index of refraction estimate for both specular and non-specular materials (Fig. 8). Unpolarized volumetric scatter is included in the model and we find that index estimates for rough metal surfaces are fairly robust to the volumetric signal contamination. The index estimates for a dielectric surface (e.g., PMMA) have more bias, although if it can be assumed that absorption is low (complex index component is zero), then the index estimates are much better.

3. Student Participation

From this funding, two PhDs and two master students were produced. One student is currently pursuing his PhD students.