Office of Naval Research (ONR)

Final Research Performance Progress Report (RPPR)

Contract Number: N000141612408

Title: Negative Optical Torque Generation in Plasmonic and Dielectric Metasurfaces

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Major goals:

The major goals of the proposed project is to explore and demonstrate the new concept of negative, zero and positive optical torque generation in plasmonic and dielectric metasurface microgears designed from the principle of Pancharatnam-Berry phase and based on spin-to-orbital angular momentum conservation of photons, by the direct observation of the controllable rotation direction and frequency of metasurface microgears, in order to study the light-matter interactions between optical angular momentum and metasurfaces and quantify the tunable optical torques with negative, zero and positive values applied on the metasurfaces due to the spin-orbit coupling. The proposed work will not only provide new approaches for fundamental optical physics studies of spin-orbit optomechanics and light-matter interactions, but also offer new opportunities for advancing many applications in the areas of optical vortex, wavefront shaping, and optical MEMS.

The specific objectives of this project include:
(1) Plasmonic and dielectric metasurfaces *q*-plates with various topological charges will be designed and analyzed with numerical simulations, by utilizing ultrathin gold nanostructures and silicon nanoantennas as the half- or quarter-wave plate elements.
(2) Nanofabrication process will be developed to fabricate the designed plasmonic and dielectric metasurface microgears with wave plate elements made of gold nanostructures and silicon nanoantennas.
(3) The optical vortex generation through the fabricated plasmonic and dielectric metasurface *q*-plates with different topological charges at optical frequencies will be measured in an optical interference setup.
(4) The mechanical rotation of the fabricated plasmonic and dielectric metasurface microgears induced by the optical torque will be characterized in water environment.

Accomplishments Under Goals:

Based on our research activities and progress in theoretical analysis, numerical simulation, sample nanofabrication and optical characterization in metasurface structures, we have focused on 5 major research topics and summarized the research results into 16 high-quality journal publications.

(1) The demonstration of complex optical beam generation by plasmonic metasurfaces:

We design and demonstrate Au and Al plasmonic metasurfaces consisting of nanoslit antennas as ultracompact beam converters to realize the optical vortex transmutation, the orbital angular momentum transformation, the vector vortex beam transformation, the generation of nondiffracting Bessel, Mathieu, and Weber vector beams, and the generation of polarization singularities. The free-space optical vortex transmutation is realized with the designed noncanonical vortex phase profiles possessing discrete rotational symmetries of finite order. The orbital angular momentum transformation of optical vortex is realized with the metasurface phase distributions derived from the caustic theory. The transformation of vector vortex beams with arbitrary polarization states and orbital angular momentum values along the beam propagation is also demonstrated. Nondiffracting Bessel, Mathieu, and Weber vector beams are generated by using ring-shaped metasurfaces by the superposition of two off-axis right-handed and left-handed circularly polarized nondiffracting scalar beams described by the Whittaker integral. The polarization singularities are directly generated by using plasmonic metasurfaces with the geometric phase profiles designed to form the Poincaré beams. Different morphologies of polarization topological structures of lemon, star, monstar, spiral, dipole and quadrupole are created by the superpositions of Laguerre–Gauss modes with different orders under orthogonal circular or linear polarization basis. Our results are promising for tailoring complex light beams, optical manipulation, and optical communication. These results are published in one Physical Review Applied paper, one Advanced Optical Materials paper, and three Scientific Reports papers. Main research activities include simulation and measurement of transmission spectra, 3D beam profiles, and vortex beam interference patterns.

(2) The demonstration of nonlinear optical beam conversion by atomically thin transition metal dichalcogenide monolayer:

We propose and demonstrate the nonlinear conversion of orbital angular momentum in atomically thin tungsten disulfide (WS_2) monolayer at both of the second- and third-harmonic frequencies of the fundamental vortex beam. We also show that by taking advantage of the symmetry properties of the crystal, the intensity and polarization state of the converted nonlinear vortex beam can be precisely controlled and determined by the polarization state of the fundamental beam. We also report a nonlinear transition metal dichalcogenide hologram with high conversion efficiency and atomic thickness made of only single nanopatterned tungsten disulfide monolayer, for producing optical vortex beams and Airy beams as well as reconstructing complex holographic images at the second harmonic frequency. In addition, we demonstrate the nonlinear generation of Hermite–Gaussian beams at second-harmonic frequencies via the binary phase manipulation on the patterned WS_2 monolayer crystals. Our results pave the way toward not only the understanding of light−matter interactions at the atomic level but the integration of 2D material devices into the next-generation photonic circuits. These results are published in Nano Letters, ACS Photonics, Journal of Optics, and

Scientific Reports. Main research activities include the measurement of nonlinear SHG and THG optical spectra, nonlinear optical images, and polarization dependent responses.

(3) The demonstration of chiral plasmonic metasurfaces with symmetry breaking:

We demonstrate broadband chiral metasurface absorbers with multiple double-rectangle resonators with large CD in absorption more than 0.5 covering the wavelength range from 1.35 μm to 1.85 μm. We also demonstrate mid-infrared chiral plasmonic metasurfaces with high CD in absorption over 0.65 in the frequency range of 50 to 60 THz, and the strong interaction with the phonon vibrational resonance of PMMA molecules at 52 THz under circularly polarized light. In addition, we demonstrate the binary-pattern chiral plasmonic metasurfaces via the micro-genetic algorithm optimization method with strong circular dichroism in absorption in the near-infrared wavelength range. The influence of geometric parameter modifications in the binary-pattern nanostructures on the circular dichroism performance is studied. We also report a unique type of 3D Janus plasmonic helical nanoaperture with direction-controlled polarization sensitivity. Circular dichroism in transmission of as large as 0.72 is experimentally realized in the forward direction due to the spin-dependent mode coupling process, however, the nanoaperture acquires giant linear dichroism in transmission of up to 0.87 in the backward direction. By encoding the Janus metasurface with the two nanoaperture enantiomers having specified rotation angles, direction-controlled polarization-encrypted data storage is demonstrated, where a binary quick-response code image is displayed in the forward direction under the circularly polarized incidence, while a distinct grayscale image is revealed in the backward direction under linearly polarized illumination. Our demonstrated chiral metasurfaces enable promising platforms for applications in energy harvesting, data encryption and decryption, and chiral sensing. The results are published in Optics Express, Nanotechnology, and Light: Science & Applications. Main research activities include simulation and measurement of transmission, reflection, absorption and CD spectra, analysis of the highly spin-dependent field distributions of chiral metasurfaces, and the chiral image capture.

(4) The determination of effective parameters of fishnet metamaterials with vortex based interferometry:

We report a new optical vortex based interferometric approach for the characterization of the effective parameters of optical metamaterials by directly measuring the transmission and reflection phase shifts from metamaterials according to the rotation of vortex spiral interference pattern. The fishnet metamaterials possessing positive, zero and negative refractive indices are characterized with the vortex based interferometry to precisely determine the complex values of effective permittivity, permeability, and refractive index. Our results will pave the way for the advancement of new spectroscopic and interferometric techniques to characterize optical metamaterials, metasurfaces, and nanostructured thin films in general. The results are published in Optics Express. Main research activities include simulation and measurement of transmission and reflection spectra, spiral interference patterns of vortex beams, and the retrieval of complex values of permittivity, permeability, and refractive index.

(5) The demonstration of in-plane anisotropic third-harmonic generation from 2D material thin flakes:

We report the anisotropic polarization-dependent third-harmonic generation (THG) from exfoliated thin GeSe and GeAs flakes due to the low in-plane lattice symmetry. It is also shown that the intensity and polarization state of THG emission can be controlled by the polarization state of pump beam. Moreover, it is demonstrated that the crystal's symmetry axes can be rapidly determined by characterizing the intensity profile of THG emission upon the excitation from radially or azimuthally polarized vector beam. The results of this study pave the way for realizing anisotropic nonlinear metasurfaces to build multiplexers, signal processors, and other prototypes for future on-chip photonic circuits. The results are published in Laser & Photonics Reviews and Scientific Reports. Main research activities include the measurement of angle-resolved polarized Raman spectra, polarization-dependent THG, and THG conversion efficiency as a function of flake thickness.

Training Opportunities:

The proposed research provides comprehensive training for graduate students and postdocs to learn and develop their expertise in the research area of optical metamaterials and metasurfaces, optical spectroscopy, optical imaging and interference. Three graduate students have been involved in the project, Leixin Ouyang, Shamim Mahmud, and Zhigang Li. Four postdocs have partially participated in the project, Yuchao Zhang, Arindam Dasgupta, Huseyin Sar, and Yang Chen. Students and postdocs have learned how to conduct scientific research independently and how to conduct collaborative research work. They have detailed full training in all the aspects of theoretical analysis, numerical design, sample nanofabrication and optical characterization, data analysis and paper writing. Students and postdoc also have opportunities to interact with leading scientists and develop team work skills through collaborations with other institutions, including the University of Missouri - Columbia, Argonne National Laboratory and Sandia National Laboratory.

Results Dissemination:

The research results are disseminated broadly through journal publications, invited talks, presentations, press release and our group websites. There are 16 high-quality journal publications in Nano Letters, ACS Photonics, Light: Science & Applications, Physical Review Applied, Laser & Photonics Reviews, Advanced Optical Materials, Scientific Reports, Optics Express, Nanotechnology, and Journal of Optics. All the publications are also posted in the PI’s group websites. The PI has given presentations on campus and several invited talks about these research works. The results will also be submitted to major optics conferences in the near future. Graduate students and postdocs work with collaborators at other universities and national laboratories, including the University of Missouri - Columbia, Argonne National Laboratory and Sandia National Laboratory. The PI continues to integrate a three-hour learning module about optical materials and structures into the thermal radiation part of the undergraduate course “Heat Transfer” (ME 3525) to enhance the curriculum and students have shown great interests to learn more about our research work. The PI has successfully developed a new graduate level course named “Advanced Optical Materials and Structures” at Missouri S&T. There are 7 PhD students enrolled in this course during the Fall 2019 semester. This new course introduces the fundamentals of nanophotonics, plasmonics and optical metamaterials, and their applications in the areas of metamaterial perfect absorbers and thermal emitters, integrated photonic circuits, optomechanics, optical communications, and optical sensors. The research results from this project have been included in the lectures successfully. All the students think that this course give them a great training in innovative thinking, open discussion, presentation skill and scientific paper writing, etc, and this course is very helpful for them to complete their PhD degree. The PI has actively participated in “Outreach and Pre-college Programs” at Missouri S&T in the past years, especially the “Summer Research Academy” program to train high school students to learn the developed six-week optics short course and project and COMSOL numerical simulation in metamaterials. The PI has also arranged the GEM GRAD Lab (Getting Ready for Advanced Degrees Lab) tours for undergraduate students (specifically from underrepresented minority backgrounds) to visit several research labs in the department including the PI’s Nanoscale Optics Lab and learn more about applying and getting into graduate school.

Honors and Awards:

Nothing to Report

Technology Transfer:

Nothing to Report

Distribution Statement:

Approved for public release; distribution is unlimited.

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Products (Publications):

1. A. Dasgupta, X. Yang, and J. Gao, "Nonlinear beam shaping with binary phase modulation on patterned WS2 monolayer," ACS Photonics, accepted (2020).

2. H. Sar, J. Gao, and X. Yang, "In-plane anisotropic third-harmonic generation from germanium arsenide thin flakes," Scientific Reports, 10, 14282 (2020).

3. S. Mahmud, D. Rosenmann, D. A. Czaplewski, J. Gao, and X. Yang, "Plasmon-phonon coupling between mid-infrared chiral metasurfaces and molecular vibrations," Optics Express, 28, 21192-21201 (2020).

4. W. Cao, J. Gao, and X. Yang, "Determination of effective parameters of fishnet metamaterials with vortex based interferometry," Optics Express, 28, 20051-20061 (2020).

5. L. Ouyang, D. Rosenmann, D. Czaplewski, J. Gao, and X. Yang, "Broadband infrared circular dichroism in chiral metasurface absorbers," Nanotechnology, 31, 295203 (2020).

6. A. Dasgupta, J. Gao, and X. Yang, "Anisotropic third-harmonic generation in layered germanium selenide," Laser & Photonics Reviews, 14, 1900416 (2020).

7. Y. Zhang, X. Yang, and J. Gao, "Generation of polarization singularities with geometric metasurfaces," Scientific Reports, 9, 19656 (2019).

8. A. Dasgupta, X. Yang, and J. Gao, "Nonlinear conversion of orbital angular momentum in tungsten disulfide monolayer," Journal of Optics, 21, 125404 (2019).

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10. A. Dasgupta, J. Gao, and X. Yang, "Atomically thin nonlinear transition metal dichalcogenide holograms," Nano Letters, 19, 6511-6516 (2019).

11. Y. Zhang, J. Gao, and X. Yang, "Optical vortex transmutation with geometric metasurfaces of rotational symmetry breaking," Advanced Optical Materials, 7, 1901152 (2019).

12. Y. Zhang, J. Gao, and X. Yang, "Spatial variation of vector vortex beams with plasmonic metasurfaces," Scientific Reports, 9, 9969 (2019).

13. Y. Zhang, X. Yang, and J. Gao, "Generation of nondiffracting vector beams with ring-shaped plasmonic metasurfaces," Physical Review Applied, 11, 064059 (2019).

14. Y. Zhang, X. Yang, and J. Gao, "Orbital angular momentum transformation of optical vortex with aluminum metasurfaces," Scientific Reports, 9, 9133 (2019).

15. A. Dasgupta, J. Gao, and X. Yang, "Second-harmonic optical vortex conversion from WS2 monolayer," Scientific Reports, 9, 8780 (2019).

16. Y. Chen, X. Yang, and J. Gao, "3D Janus plasmonic helical nanoapertures for polarization-encrypted data storage," Nature - Light: Science & Applications, 8, 45 (2019).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
09/14/2020	Final	Jun 2019 - Sep 2020

4. TITLE AND SUBTITLE
Negative Optical Torque Generation in Plasmonic and Dielectric Metasurface

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-16-1-2408

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goals of this project is to explore and demonstrate the optical vortex beam generation and the optical torque manipulation in plasmonic and dielectric metasurfaces, which are designed from the principle of Pancharatnam-Berry phase and based on spin-to-orbital angular momentum conservation of photons, in order to study the light-matter interactions with plasmonic and dielectric metasurfaces.

15. SUBJECT TERMS
Optical vortex, plasmonic metasurface, dielectric metasurface, optical torque

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Xiaodong Yang
					19b. TELEPHONE NUMBER *(Include area code)*
			UU	8	573-341-6273