AFRL-AFOSR-VA-TR-2023-0046

Plasmon-induced Electric Effects in Plasmonic Surfaces

Noginova, Natalia
NORFOLK STATE UNIVERSITY
700 PARK AVE STE 310
NORFOLK, VA, 23504
USA

10/12/2022
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED**	
20221012	Final	**START DATE** 20180715	**END DATE** 20220714

4. TITLE AND SUBTITLE
Plasmon-induced Electric Effects in Plasmonic Surfaces

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
	FA9550-18-1-0417	61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Natalia Noginova

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NORFOLK STATE UNIVERSITY
700 PARK AVE STE 310
NORFOLK, VA 23504
USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2023-0046

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The project "Plasmon-Induced Electric Effects in Plasmonic Surfaces" has been devoted to the exploration of plasmon-induced electric effects in metal nanostructured systems, in order to better understand the nature of these effects and explore possible applications. The plasmon related enhancement in photoinduced electric currents has been studied in metal structures and metasurfaces with various profile geometries. It was found that 1D periodically modulated structures with relatively high amplitudes of profile modulation show a sharp switching in the photovoltage polarity around the surface plasmon polariton resonance conditions. This finding presents new opportunities for applications, in particular, in plasmonic-based sensing allowing one to use a compact electric detection instead of bulk optical setup. It was demonstrated that small changes in the refractive index (Î"n=0.001) or a presence of a monolayer on the surface could be ultimately resolved with switching in photovoltage polarity, which is not possible with traditional optical detection. Systematic experimental data has been obtained on the photoinduced electric effects which take place in various materials (gold, silver, aluminum,
copper, platinum and permalloy) under plasmon resonance conditions in the dependence on the wavelength of illumination and surface geometry (films or gratings). Experiments show that the photoresponses exhibit a general decrease with an increase in the wavelength and strongly vary depending upon the material in the contrast to the theoretical predictions of the existing plasmonic pressure model.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	11

19a. NAME OF RESPONSIBLE PERSON	**19b. PHONE NUMBER** *(Include area code)*
ARJE NACHMAN	426-8427

Federal Agency and Organization Element to Which Report is Submitted:

AFOSR

Federal Grant or Other Identifying Number Assigned by Agency:

FA9550-18-1-0417

Project Title:

Plasmon-Induced Electric Effects in Plasmonic Surfaces

PD/PI Name:

- Natalia Noginova, Principal Investigator, Professor, Department of Physics, NSU
- Mikhail A Noginov, Co-Principal Investigator, Professor, Department of Physics, NSU

Recipient Organization:

Norfolk State University

Project/Grant Period:

07/15/2018 - 07/14/2022

Reporting Period:

07/15/2018 - 07/14/2022

Accomplishments

What are the major goals of the project?

This project is devoted to the exploration of plasmon-induced electric effects in various plasmonic systems. The goals of the project are:
(1) Better understanding the nature of these effects;
(2) Development of plasmonic structures and metasurfaces with strong and controllable plasmon-related electric responses; and
(3) Exploration of approaches which would allow one to utilize these effects, including compact electric monitoring of plasmonic excitations in metal nanostructures.

What was accomplished under these goals and objectives

Major results and corresponding publications

1. The plasmon-related enhancement in photoinduced electric currents (plasmon drag effect, PLDE) has been studied in various geometries and found to be the most significant in systems with strongly modulated surface profiles [1,2]. In 1D periodically modulated structures with high amplitude of profile modulation, the photoinduced voltages demonstrated sharp switching in polarity at the surface plasmon polariton (SPP) resonance conditions. The spectral behavior and dependence on the sample orientation indicate a possible role of coupling between SPP and localized plasmons in the photoinduced electric signals.
Significant result: development of structures with strong and controllable plasmon-induced electric responses. *This corresponds to Goal 2 of the Project.*

[1] D. Keene; T. Ronurpraful; N. Nogniova, "Plasmon related electrical effects in strongly modulated metasurfaces, "Proc. SPIE 11080, Metamaterials, Metadevices, and Metasystems 2019, 110801C (5 September 2019); https://doi.org/10.1117/12.2532069
[2] T. Ronurpraful, D. Keene, and N. Noginova, "Plasmon drag effect with sharp polarity switching," New Journal of Physics. 22 (4) 043002 (2020)

2. We demonstrated the use of this feature for compact electric detection of environmental changes [2-4]. Small changes in the refractive index ($\Delta n = 0.001$) [3] or a presence of a monolayer on the surface [4] are ultimately resolved with the photovoltage polarity.
Significant result: We demonstrated that the switching in the photovoltage polarity in our structures presents new opportunities for sensing applications. *This corresponds to Goal 3 of the Project.*

[3] T. Ronurpraful, N. Jerop, A. Koech, K. Thompson, and N. Noginova, "Electrical detection of surface modification in plasmonic metasurfaces", SPIE-Metamaterials, Metadevices, and Metasystems 2020, 2020
[4] T. RonurPraful, N Jerop, A Koech, K Thompson, N Noginova, "Extreme sensitivity of plasmon drag to surface modification, " J. Phys. D: Appl. Phys. 54 035307 (2021).

3. Based on the electrodynamic hydrodynamic momentum loss approach, light-induced effective forces were theoretically estimated in plasmonic material as the function of the wavelength of illumination and material parameters [5,6]. The magnitudes and spectral behavior of the plasmonic pressure force, striction force, and surface charge density are estimated for several materials and typical experimental conditions. *This corresponds to Goal 1 of the Project.*

4. Systematic experimental data has been obtained on the plasmon drag in various materials (gold, silver, aluminum, copper, platinum and permalloy) in the dependence on the wavelength of illumination and material geometry (films or gratings) [6]. Experiments show that the photoresponses exhibit a general

decrease with an increase in the wavelength and strongly vary depending upon the material in the contrast to the theoretical predictions of the simplified plasmonic pressure model.

Significant result: The obtained data provides an information for an optimal choice of material/structure for applications and for further development of the theoretical approach to light-matter interaction in plasmonic systems. *This corresponds to Goals 1-3 of the Project.*

[5] D. Keene, P. Fortuno, N. Noginova, "Photocurrents in Plasmonic Metals. Spectral and material dependence," APS March Meeting, Chicago, IL, March 14-18, 2022, #A66.009

[6] D. Keene, P. Fortuno, M. Durach and N. Noginova, "Photoinduced electric effects in various plasmonic materials," J. Phys. Cond. Matt. 2022 (accepted)

5. Systems with both plasmonic properties and magnetic in-plane anisotropy have been developed and characterized for studies of possible plasmon-induced magnetization [7-9]. Electron magnetic resonance experiments and theoretical simulations confirmed the anisotropy and the presence of spin-wave resonances with wave-vectors of the same scale as plasmonic wave-vectors, as determined by parameters of profile-modulated structures. *This corresponds to Goal 3 of the Project.*

Significant result: development of the structures promising for spintronics and magnetoplasmonics.

[7] M. Shahabuddin, N. Noginova, "Plasmonic System with In-Plane Magnetic Anisotropy for Plasmon Based Magnetic Switching," OSA Techn. Digests CLEO: QELS_Fundamental Science, San Jose CA 2019, paper #JW2A. 59.

[8] Yu. Gubanova, M. Shahabuddin, V. Gubanov, D. Keene, M. A. Rab, A. V. Sadovnikov, N. Noginova, "Magnonic and plasmonic effects in permalloy metasurfaces," SPIE Optics & Photonics Conference, August 1-5 2021, San Jose CA.

[9] N. Noginova, V. Gubanov, M. Shahabuddin, Yu. Gubanova, S. Nesbit, V. V. Demidov, V. A. Atsarkin, E. N. Beginin, A. V. Sadovnikov, "Ferromagnetic Resonance in Permalloy Metasurfaces", Applied Magnetic Resonance **52**, 749–758 (2021).

6. We experimentally found that in permalloy structures, the photoinduced electric signal depends on magnetic field with a characteristic hysteresis determined by parameters of the structure. [10,11].

Significant result: Coupling of magnetic, electric and optical/plasmonic effects has been demonstrated. This finding can find applications in spintronics, plasmonic circuits with magnetic control, and optical manipulation of electron spins.

This corresponds to Goal 3 of the Project.

[10] M Shahabuddin, DW Keene, M Durach, VS Posvyanskii, VA Atsarkin, N. Noginova "Magnetically dependent plasmon drag in permalloy structures, "JOSA B 38 (6), 2012-2018 (2021)

[11] D. Keene, Md. Rab, M. Shahabuddin and N. Noginova, " Magnetic control of photovoltages in permalloy based metasurfaces," SPIE 2022, # 12195-43.

7. Significant result: We demonstrated a possibility to control electrochemical reactions with plasmonic environment and additional light illumination [12-14]. Enhancement of the electrochromic polymer performance [12], faster charge transfer [13] and a possibility to control electrochemical deposition with light [14] in plasmonic environment have been demonstrated. *This corresponds to Goal 3 of the Project*

[12] M. Shahabuddin, T. McDowell, C.E. Bonner, N. Noginova," Enhancement of Electrochromic Polymer Switching in Plasmonic Nanostructured Environment," ACS Appl. Nano Mater., 2 (3), pp 1713–1719 (2019).

[13] M. Shahabuddin, A. K. Wilson, A. C. Koech, and N. Noginova, "Probing Charge Transport Kinetics in a Plasmonic Environment with Cyclic Voltammetry," ACS Omega **6**, 50, 34294–34300 (2021).

[14] P. Fortuno, A.Wilson, N.Noginova, " Control of Electrochemical Reactions and Film Deposition with the Plasmonic Environment and Light Illumination," MRS Spring Meeting, Honolulu, Hawaii, May 8-13 2022, # PEQ10.09.11.

Other achievements:

Three students participating in the research defended their Ph.D. Dissertations. Two undergraduate students involved in the research got accepted to our Materials Science and Engineering Ph.D program.

Ph.D. Dissertations defended in Material Science and Engineering

1. David W Keene, "Electric Effects in Plasmonic Structures. Experiment and Theory", 2022, NSU

Dissertation presents results of experimental and theoretical studies of the plasmon-induced electric voltages in various materials and geometries toward a better understanding of the origin of the plasmon drag and bringing new findings into the field. *Relevance to the project: Goals 1-3.*

2. Tejaswini RonurPraful, "Novel Approaches in Plasmon-based Sensing", 2021, NSU .

Dissertation presents results of the study of the plasmon drag effect in various geometries and exploration of new approaches to biomedical sensing based on 1D plasmonic structures and plasmon-induced electric effects. *Relevance to the project: Goals 2-3*

3. Mohammad Shahabuddin, "Control of Electrochemical and Magnetic Phenomena with Metamaterials", 2021, NSU.

Dissertation discusses two new findings: (i) coupling plasmonic electric and magnetic effects in permalloy structures, and (ii) possibility to control electrochemical reactions with plasmonics. *Relevance to the project: Goals 2-3.*

What opportunities for training and professional development has the project provided?

The project involves participation of eight graduate students, who received training in nanofabrication and characterization, optical characterization and experiment, lasers, electron magnetic resonance, COMSOL simulation software, AFM and electrochemical experiments.

Graduate students closely involved in this research attended and presented at MRS, APS and CLEO conferences.

Three students successfully defended their Ph.D. dissertations based on the results of this work. Two students plan their defenses (M.S.) in near future.

Undergraduate students participating in the research receive training in basic fabrication and characterization.

The results and ideas of this research were used to enhance teaching of the graduate Nanotechnology course.

Have the results been disseminated to communities of interest? If so, please provide details.

The results have been published in the scientific journals and presented at conferences. The support from the agency has been acknowledged.

The publications include 29 papers in peer-reviewed journals and 16 of conference proceedings and technical digests. We presented 48 talks at the national and international conferences, such as CLEO, MRS, APS and SPIE.

Products

Publications in peer-reviewed journals

1. A. Vaskin, S. Mashhadi, M.l. Steinert, K. E. Chong, D. Keene, S. Nanz, A. Abass, E. Rusak, D.-Y. Choi, I. Fernandez-Corbaton, T. Pertsch, C. Rockstuhl, M. A. Noginov, Y.S. Kivshar, D. N. Neshev, N. Noginova, I. Staude, "Manipulation of magnetic dipole emission from Eu3+ with Mie-resonant dielectric metasurfaces", Nano letters 19 (2), 1015-1022 (2019).
2. M. Shahabuddin, T. McDowell, C.E. Bonner, N. Noginova," Enhancement of Electrochromic Polymer Switching in Plasmonic Nanostructured Environment," ACS Appl. Nano Mater. 2 (3), pp 1713–1719 (2019).
3. S. Mashhadi, M. Durach, D. Keene, N. Noginova, "Control of magnetic dipole emission with surface plasmon polaritons," OSA Continuum 2, , pp. 1342-1349 (2019).
4. E. K. Tanyi, E. Harrison, C. On, M. A. Noginov, "Coupling of the First and Second Excited States of R6G Dye with the Fabry–Perot Cavity", Physica Status Solidi B, 256 (3), 1800045 (2019). doi: 10.1002/pssb.201800045
5. E.K. Tanyi, S. Mashhadi, C. On, Md O. Faruk, E. Harrison, N. Noginova, M.A. Noginov, "Plasmonic laser with distributed feedback, "Appl. Phys. Lett. 115, 151103 (2019).
6. T. Ronurpraful, N. Jerop, N. Noginova, "Ultra-sensitive plasmonic sensing based on gold nanostrip arrays," Optics letters 44 (17), 4199-4202 (2019).
7. V. N. Peters, Md Omar Faruk, J. Asane, R. Alexander, D. A. Peters, S. Prayakarao, S. Rout, M. A. Noginov, "Effect of Strong Coupling on Photodegradation of the Semiconducting Polymer P3HT", Optica 6, 318-325 (2019).
8. Joshua Kwame Asane, Vanessa Nicole Peters, Rohan Alexander, Tylisia Wallace, D'Angelo Peters, Mikhail A. Noginov, "Study of electrical conductivity of the poly(3 hexylthiophene-2, 5-diyl) polymer in resonant Fabry–Perot cavities," J. Nanophoton. 13(2), 026007 (2019), doi: 10.1117/1.JNP.13.026007.
9. V. N. Peters, C. Yang, S. Prayakarao, and M. A. Noginov, "Effect of metal–dielectric substrates on chemiluminescence kinetics", Journal of the Optical Society of America B, 36, E132-E138 (2019). https://doi.org/10.1364/JOSAB.36.00E132
10. Srujana Prayakarao, Deionjalei Miller, Devon Courtwright, Carl E. Bonner, and Mikhail A. Noginov, "Non-resonant enhancement of spontaneous emission of HITC dye in metal-insulator-metal waveguides," J. Opt. Soc. Am. B 36, 2312-2316 (2019). https://doi.org/10.1364/JOSAB.36.002312.
11. Srujana Prayakarao, Samantha R. Koutsares, Carl E. Bonner, and Mikhail A. Noginov, "Effect of nonlocal metal–dielectric environments on concentration quenching of HITC dye", JOSA B, 36, 3579-3587 (2019). https://doi.org/10.1364/JOSAB.36.003579
12. Vanessa N. Peters, Srujana Prayakarao, Samantha R. Koutsares, Carl E. Bonner, and Mikhail A. Noginov, "Control of Physical and Chemical Processes with Nonlocal Metal− Dielectric Environments", ACS Photonics 6, 3039−3056 (2019). DOI: 10.1021/acsphotonics.9b00734.
13. S. R. Koutsares, E. K. Tanyi, S. J. Daniel, R. S. Savelev, M. Rahmani, D. Neshev, I. V. Shadrivov, and M. A. Noginov "Low-loss volume modes in a lamellar hyperbolic metamaterial slab", JOSA B, 37, 1065-1072 (2020). https://doi.org/10.1364/JOSAB.376752

14. J. K. Asane, M. A. Noginov, “Concentration dependence of two-photon absorption in PMMA polymeric films doped with rhodamine laser dyes”, JOSA B, 37, 3108-3115 (2020). https://doi.org/10.1364/JOSAB.399318

15. Md Omar Faruk, Nelly Jerop, Mikhail A. Noginov, “Emission of R6G dye in Fabry–Perot cavities in weak and strong coupling regimes”, JOSA B, 37, 3200-3212 (2020). https://doi.org/10.1364/JOSAB.403612

16. Sangeeta Rout, Zhen Qi, Ludvig S. Petrosyan, Tigran V. Shahbazyan, Monika M. Biener, Carl E. Bonner and Mikhail A. Noginov, “Effect of Random Nanostructured Metallic Environments on Spontaneous Emission of HITC Dye”, Nanomaterials, 10, 2135 (2020). doi:10.3390/nano10112135

17. T. Ronurpraful, D. Keene, and N. Noginova, "Plasmon drag effect with sharp polarity switching," New Journal of Physics. 22 (4) 043002 (2020).

18. T. RonurPraful, N Jerop, A Koech, K Thompson, N Noginova, “Extreme sensitivity of plasmon drag to surface modification, “ J. Phys. D: Appl. Phys. 54 035307 (2021).

19. V. A. Atsarkin, N. Noginova, “Electron Spin Resonance on the Border Between Para-and Ferromagnetism: Quantum versus Classical,” Apl. Magn. Res. 51, 1467–1480(2020) (2020)

20. S. Rout, Z. Qi, M.M Biener, D.Courtwright, J.C Adrien, E. Mills, M. Shahabuddin, N. Noginova, M.l A Noginov, “Nanoporous gold nanoleaf as tunable metamaterial”, Scientific Reports, 11, 1795 (2021). https://doi.org/10.1038/s41598-021-81128.

21. S. Koutsares, L. S. Petrosyan, S. Prayakarao, D. Courtwright, C. E. Bonner, T. V. Shahbazyan, M. A. Noginov, “Effect of metallic substrates and cavities on emission kinetics of dye-doped polymeric films”, JOSA B 38, 88-94 (2021). https://doi.org/10.1364/JOSAB.409998

22. J. B. Khurgin, M. A. Noginov, “How Do the Purcell Factor, the Q-Factor, and the Beta Factor Affect the Laser Threshold?, Laser & Photonics Reviews, 2000250 (2021). https://doi.org/10.1002/lpor.202000250.

23. D. Courtwright, S. Rout, J. Adrien, M. A Noginov, “Effect of flexural stress on fabrication and optical properties of a composite photonic material”, Journal of Nanophotonics 15, 026002 (2021). doi.org/10.1117/1.JNP.15.026002

24. M Shahabuddin, DW Keene, M Durach, VS Posvyanskii, VA Atsarkin, N. Noginova "Magnetically dependent plasmon drag in permalloy structures, "JOSA B 38 (6), 2012-2018 (2021).

25. N. Noginova, V. Gubanov, M. Shahabuddin, Yu. Gubanova, S. Nesbit, V. V. Demidov, V. A. Atsarkin, E. N. Beginin, A. V. Sadovnikov, "Ferromagnetic Resonance in Permalloy Metasurfaces", Applied Magnetic Resonance **52**, 749–758 (2021).

26. M. Shahabuddin, A. K. Wilson, A. C. Koech, and N. Noginova, "Probing Charge Transport Kinetics in a Plasmonic Environment with Cyclic Voltammetry," ACS Omega **6**, 50, 34294–34300 (2021).

27. Joshua K. Asane, Md G. R. Chowdhury, Kanij M. Khabir, Viktor A. Podolskiy, and Mikhail A. Noginov, “Stimulated emission in vicinity of the critical angle”, Appl. Phys. Lett. 119, 031102 (2021); doi: 10.1063/5.0051901.

28. Sangeeta Rout , Samantha R. Koutsares, Devon Courtwright, Ezekiel Mills, Ayanna Shorter, Srujana Prayakarao, Carl E. Bonner and Mikhail A. Noginov, “Effect of nanoscale dielectric environments on concentration quenching”, Nanophotonics, 000010151520210132. (2021) https://doi.org/10.1515/nanoph-2021-0132

29. Sangeeta Rout, Vanessa N Peters, Sangram K Pradhan, Carl E Bonner, Mikhail A Noginov, “Emission kinetics of HITC laser dye on top of arrays of Ag nanowires”, Nanophotonics, 2021, pp. 000010151520210374. https://doi.org/10.1515/nanoph-2021-0374.

30. D. Keene, P. Fortuno, M. Durach and N. Noginova, "Photoinduced electric effects in various plasmonic materials," J Phys. Condens. Matter,, (2022) Sep 7;34(45). doi: 10.1088/1361-648X/ac8cc7.

Conference proceedings and digests

1. D. Keene; T. Ronurpraful; N. Nogniova, “Plasmon related electrical effects in strongly modulated metasurfaces, “Proc. SPIE 11080, Metamaterials, Metadevices, and Metasystems 2019, 110801C (5 September 2019); https://doi.org/10.1117/12.2532069
2. J. K. Asane, A. Bullock, M. Clemmons, N. Noginova, and M. A. Noginov, "Development of Near-Infrared Rare Earth Doped Organic Materials for Nanophotonics Applications," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2019), paper FTh4M.6.
3. S. Koutsares, S. Prayakarao, D. Courtwright, C. E. Bonner, and M. A. Noginov, "Effect of Fabry-Perot Cavities on Concentration Quenching," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2019), paper JTh2A.20.
4. S. Rout, M. Biener, Z. Qi, C. E. Bonner, T. V. Shahbazyan, and M. A. Noginov, "Light-Matter Interaction in Disordered Metal-Dielectric Environments," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2019), paper FTu3D.4.
5. S. R. Koutsares, L. S. Petrosyan, D. Courtwright, S. Prayakarao, C. E. Bonner, T. V. Shahbazyan, M. A. Noginov, “Control of Concentration Quenching with Metallic Substrates and Cavities”, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2020), paper FM1D.4
6. T Ronurpraful, D Keene, N Noginova “Electrical Detection of Surface Plasmons for Sensing Applications CLEO: QELS_Fundamental Science, #FTh4C. 7, San Jose CA, 2019
7. M. Shahabuddin, N. Noginova, “Plasmonic System with In-Plane Magnetic Anisotropy for Plasmon Based Magnetic Switching,” CLEO: QELS_Fundamental Science, JW2A. 59, San Jose CA, 2019.
8. S. Rout, Z. Qi, M. Biener, D. Courtwright, J. Adrien, M. Shahabuddin, C. E. Bonner, N. Noginova, and M. A. Noginov, “Nanoporous Gold Nanoleaf as Tunable Metamaterial”, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2020), paper JTh2C.7.
9. Md Omar Faruk, Nelly Jerop, Mikhail A. Noginov, “Emission in Fabry-Perot Cavities in Weak and Strong Coupling Regimes”, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2020), paper JW2D.6

10 T. Ronurpraful, N. Jerop, and N. Noginova, “Extreme sensitivity of plasmon drag to surface modification,“ OSA Techn. Digests, CLEO: QELS_ Fundamental Science, 2020, paper #FM4Q.

11. M. Shahabuddin, D. Keene, and N. Noginova, “Magneto-dependent plasmon drag in permalloy structures,“ OSA Techn. Digests CLEO: QELS_Fundamental Science, 2020, paper #JTu2D.14
12. Sangeeta Rout, S. Koutsares, D. Courtwright, E. Mills, A. Shorter, S. Prayakarao, C. Bonner, Mikhail Noginov, “Effect of Thickness of a Dye-Doped Polymeric Film on the Concentration Quenching of Luminescence”, CLEO Conference (virtual), May 9 – May 14, 2021, paper JW1A.96.
13. Joshua Asane, Md Golam Chowdhury, Kanij Khabir, Viktor Podolskiy, Mikhail Noginov, ”Stimulated Emission With Evanescent Gain in the Total Internal Reflection Geometry”, CLEO Conference (virtual), May 9 – May 14, 2021, paper JW1A.128.
14. Md Golam Rabbani Chowdhury, Ayanna Shorter, Sangeeta Rout, Mikhail A. Noginov, “Anomalous Dips in Reflection Spectra of Polymers Deposited on Plasmonic Metals”, CLEO Conference, San JOSE, CA, USA and virtual, May 15 – May 19, 2022, paper JTu3B.14.
15. Md Golam Rabbani Chowdhury, Shamaar R. Howard, Kanij Mehtanin Khabir, Mikhail A. Noginov, “Dispersion in Reflection and Emission of Dye Molecules Strongly Coupled to Surface Plasmon Polaritons”, CLEO Conference, San JOSE, CA, USA and virtual, May 15 – May 19, 2022, paper FTh2B.2.

16. A. Wilson, P. Fortuno, M. Shahabuddin, N. Noginova, "Effect of electrochromic polymer switching on surface plasmon polaritons," SPIE Proceedings 2022 (accepted).

Conference presentation without technical digests or proceedings

1. M Shahabuddin, C Bonner, N Noginova, "Effects of Nanostructured Plasmonic Environment on Electrochromic Polymer Switching," Bulletin of the American Physical Society, # V21.00012, APS March Meeting, Boston MA 2019.
2. S. Mashhadi, M. Durach, D. Keene, N. Noginova, "Plasmon-Enhanced Emission and Quenching of Magnetic Emitters, # EP12.03.10, MRS Spring Meeting, Phoenix AZ 2019.
3. M Shahabuddin, C Bonner, N Noginova, S. Mashhadi, "Effects of Nanostructured Plasmonic Environment on Electrochromic Polymer Switching," #EP12.07.02, MRS Spring Meeting, Phoenix AZ 2019.
4. V. N. Peters, S. Prayakarao; C. Yang, Md O. Faruk, J. K. Asane, S. Rout, M. A. Noginov, "Control of Chemical reactions with nonlocal metal-dielectric environments", Nanometa 2019, 7th International Topical Meeting on Nanophotonics and Metamaterials, Seefeld, Tirol, Austria 3-6 January 2019, paper SAT2s.3 *(invited)*.
5. S. Koutsares, S. Prayakarao, D. Courtwright, S. Rout, M. Biener, Z. Qi, C. E. Bonner, M. A. Noginov, "Control of Emission and Energy Transfer with Metamaterials, Plasmonic Structures and Cavities"; Bulletin of the American Physical Society, APS March Meeting 2019 (March 4–8, 2019, Boston, Massachusetts), paper #V21.00001 *(invited).*
6. J. B. Khurgin, M. A. Noginov, "Miniature lasers: what does and what does not matter?" *SPIE Optics & Photonics*, Aug. 11-15, 2019, San Diego, CA, paper 11080-7 *(invited)*.
7. D. Courtwright, S. Koutsares, S. Prayakarao, C. Bonner, Mikhail A. Noginov, "Effect of non-local metal-dielectric environments on concentration quenching and spontaneous emission" *SPIE Optics & Photonics*, Aug. 11-15, 2019, San Diego, CA, paper 11080-105.
8. M. A. Noginov, S. Prayakarao, S. R. Koutsares, S. Rout, D. Courtwright, C. E. Bonner, "Effects of inhomogeneous metal-dielectric environments on spontaneous emission and energy transfer" *SPIE Optics & Photonics*, Aug. 11-15, 2019, San Diego, CA, paper 11091- 4 *(invited)*.
9. S. Koutsares, S. Prayakarao, D. Courtwright, C. E. Bonner, M. A. Noginov, L. S. Petrosyan and T. V. Shahbazyan, "Effect of Fabry-Perot Cavities on Concentration Quenching", Progress in Nanotechnology, 2019 NSF Nanoscale Science and Engineering Grantees Conference, December 9-10, 2019, The Westin Alexandria - Alexandria, VA.
10. T. Ronurpraful, N. Jerop, and N. Noginova, "Extreme sensitivity of plasmon drag to surface modification," OSA Techn. Digests, CLEO: QELS_ Fundamental Science, 2020, paper #FM4Q.8
11. M. Shahabuddin, D. Keene, and N. Noginova, "Magneto-dependent plasmon drag in permalloy structures," OSA Techn. Digests CLEO: QELS_Fundamental Science, 2020, paper #JTu2D.14
12. S. Rout, Z. Qi, M. Biener, J. Adrien, M. Shahabuddin, C. E. Bonner, N. Noginova, M. A. Noginov, "Nanoporous Gold Nanoleaf as Tunable Metamaterial, "OSA Techn. Digests CLEO: QELS_Fundamental Science, 2020, paper # JTh2C.7.
13. T. Ronurpraful, N. Jerop, A. Koech, K. Thompson, and N. Noginova, "Electrical detection of surface modification in plasmonic metasurfaces", SPIE-Metamaterials, Metadevices, and Metasystems 2020, 2020.
14. Vanessa N. Peters, Srujana Prayakarao, Samantha R. Koutsares, Sangeeta Rout, Carl E. Bonner and Mikhail A. Noginov, "Control of Physical Phenomena with Nonlocal Metal−Dielectric Environments" Metanano, online conference https://metanano.itmo.ru, Sept. 14-18, **2020 (*keynote*).**
15. M. A. Noginov, "Control of emission and energy transfer with nonlocal metal-dielectric environments", The Triangle Hard Matter Workshop hosted by Duke Materials Initiative, online conference, December

8, 2020 (*invited*)

16. S. Rout, Z. Qi, M. Biener, D. Courtwright, J. Adrien, M. Shahabuddin, C. E. Bonner Jr., N. Noginova, M. A. Noginov, "Tunable optical properties of nanoporous gold leaf metamaterials," Proc. SPIE 11460, Metamaterials, Metadevices, and Metasystems 2020, 1146023 (20 August 2020); https://doi.org/10.1117/12.2571003
17. D. Keene, M. Shahabuddin, T. Ronurpraful, M. Durach and Noginova, N., Plasmon-related electric effects in various plasmonic materials. Bulletin of the American Physical Society, March 2021 #S41.00007.
18. J. Munga, T. Ronurpraful, D. Keene, Md. Rab, N. Jerop, F. Bett, M. Durach and N. Noginova, Enhancement of Electric and Magnetic emission in Langmuir Blodgett films and sandwich structures with Eu3+ ions. Bulletin of the American Physical Society, March 2021.
19. A. Wilson, M. Shahabuddin, Md. Rab, J. Grace, N . Noginova, "Probing charge kinetics in plasmonic environment with cycllic voltammetery, " Material Research Society Meeting, April 2021
20. Yu. Gubanova, M. Shahabuddin, V. Gubanov, D. Keene, M. A. Rab, A. V. Sadovnikov, N. Noginova, "Magnonic and plasmonic effects in permalloy metasurfaces," SPIE Optics & Photonics Conference, August 1-5 2021, San Jose CA.
21. J. Munga, M.A. Rab, Maxim Durach, and N. Noginova, "Control of Electric and Magnetic Emission in Flat and Profile Modulated Plasmonic Structures," MRS Fall Meeting, Dec. 2021 (online)
22. Md. A. Rab, J. Munga1, N. Noginova, M. Durach, " Magnetic dipole emission and effect of gap plasmons in metal-dielectric-metal structures, " MRS Fall Meeting, Dec. 2021 (online).
23. Mikhail A. Noginov, "Control of Physical Phenomena with Nonlocal Metal-Dielectric Environments", Strong Coupling with Organic Molecules (SCOM) virtual conference, April 26 – April 28, 2021 (original intended location: Gothenbirg, Sweden), *invited*.
24. Sangeeta Rout, Samantha R. Koutsares, Srujana Prayakarao, Devon Courtwright, Vanessa Peters, Zhen Qi, Lyudvig S. Petrosyan, Tigran V. Shahbazyan, Monika M. Biener, Carl E. Bonner Jr., and Mikhail A. Noginov "Effect of metal-dielectric environments on spontaneous emission and concentration quenching of HITC laser dye", Proc. SPIE 11797, Plasmonics: Design, Materials, Fabrication, Characterization, and Applications XIX, 117971I (1 August 2021); https://doi.org/10.1117/12.2594768, *invited*
25. Devon Courtwright, Sangeeta Rout, Jakeem Adrien, Mikhail Noginov, "Effect of flexural stress on fabrication and optical properties of a composite photonic material", Proc. SPIE. 11795, Metamaterials, Metadevices, and Metasystems 2021, 3 August 2021.
26. D. Keene, P. Fortuno, M. Durach, N. Noginova, "Plasmon-induced electric effects in various materials. Theory and experiment," MRS Fall Meeting, Dec. 2022 (online).
27. Md. Rab, J. Munga, N. Noginova, "Magnetic dipole emission in profile-modulated metal-dielectric-metal structures", APS March Meeting, Chicago, March 14-18, 2022, #W17009
28. J. Munga, Md. Rab, C.Yang, N. Noginova, " Highly luminescent monolayer films with rare earth emitters in plasmonic environment," APS March Meeting, Chicago, March 14-18, 2022, #A66.012:
29. D. Keene, P. Fortuno, N. Noginova, "Photocurrents in Plasmonic Metals. Spectral and material dependence," APS March Meeting, Chicago, IL, March 14-18, 2022, #A66.009.
30. P. Fortuno, A.Wilson, N.Noginova, " Control of Electrochemical Reactions and Film Deposition with the Plasmonic Environment and Light Illumination," MRS Spring Meeting, Honolulu, Hawaii, May 8-13 2022, # PEQ10.09.11
31. Leila Hesami, Chi Yang, Elias Anwar, Mikhail A. Noginov, "Effect of metal-dielectric environments on photopolymerization of the [2,2′-bi-1H-indene]-1,1′-dione-3,3′-diyldiheptanoatecarboxylate monomer", 2022 MRS Spring Meeting and Exhibit, May 8 -13.; Honolulu, Hawaii, USA.

32. K. M. Khabir, M. Shahabuddin, N. Noginova, M. A. Noginov, "Workfunction studies of constituents of Fabri-Perot cavities and MIM waveguides", 2022 MRS Spring Meeting and Exhibit, May 8 -13.; Honolulu, Hawaii, USA.

Participants

Noginova, Natalia, PD/PI; Noginov, Mikhail A, Co PD/PI

Graduate Students: Keene, David; Fortuno, Paula; Rab, Md. A; Ronurpraful, Tejaswini; Shahabuddin, Mohammad; Mashhadi, Soheila; Wilson Ashleigh; Rout, Sangeeta.

Undergraduate students: Furlow, Tori, Graham, Jordan; Howard, Shamaar; Nesbit, Sean; McDowell, Thomas; Jerop, Nelly; Koech, Ashah.

Impacts

What is the impact on the development of the principal discipline(s) of the project?

- Better understanding of optical and plasmonic behavior of nanosructured systems, further development of the fabrication and characterization methods.

- It was shown that plasmon-induced electric effects could not be fully explained in frames of the simplified electromagnetic loss approach. Experimental data have been obtained on the photovoltages as the function of the illumination wavelength in various materials and geometries for further development of the theoretical description.

- Structures with the strong and predictable plasmon drag effects have been developed.

- New finding - strong magnetodependence of the plasmon drag in systems with both plasmonic and magnetic properties -can lead to new insights of light-matter interaction in plasmonic conditions

What is the impact on other disciplines?

- Possibilities to affect/ control physical and chemical processes with plasmonic environment and plasmonic excitations can bring new opportunities for research and applications in various fields

- We show that the plasmon drag effect can be used in biomedical/environmental sensing for compact high-sensitivity electric detection instead of bulk optical setup.

What is the impact on the development of human resources?

Graduate and undergraduate students received training in various fabrication and characterization methods. The research results and training obtained contributed to the successful defenses of three Ph.D. Dissertations this year. Undergraduate students involved in the research plan to choose graduate programs in future.

What was the impact on teaching and educational experiences?

Several graduate students received basic training in numerical simulation with COMSOL using the models used in this project. The ideas of this project and related materials were used to enhance the graduate course in Materials for Nanotechnology.

What is the impact on physical resources that form infrastructure?

Based on the results and new findings from this project, a proposal to NSF has been submitted for the acquisition of a new Electron Spin Resonance Spectrometer. It is awarded. The instrumentation will be installed in near future.

PROJECT OUTCOMES

The project "Plasmon-Induced Electric Effects in Plasmonic Surfaces" has been devoted to the exploration of plasmon-induced electric effects in metal nanostructured systems, in order to better understand the nature of these effects and explore possible applications.

The plasmon-related enhancement in photoinduced electric currents has been studied in metal structures and metasurfaces with various profile geometries. It was found that 1D periodically modulated structures with relatively high amplitudes of profile modulation show a sharp switching in the photovoltage polarity around the surface plasmon polariton resonance conditions. This finding presents new opportunities for applications, in particular, in plasmonic-based sensing allowing one to use a compact electric detection instead of bulk optical setup. It was demonstrated that small changes in the refractive index ($\Delta n=0.001$) or a presence of a monolayer on the surface could be ultimately resolved with switching in photovoltage polarity, which is not possible with traditional optical detection.

Systematic experimental data has been obtained on the photoinduced electric effects which take place in various materials (gold, silver, aluminum, copper, platinum and permalloy) under plasmon resonance conditions in the dependence on the wavelength of illumination and surface geometry (films or gratings). Experiments show that the photoresponses exhibit a general decrease with an increase in the wavelength and strongly vary depending upon the material in the contrast to the theoretical predictions of the existing plasmonic pressure model. The obtained data provide an information for an optimal choice of material and illumination conditions for a particular application and for further development of the theoretical approach to light-matter interaction and electron dynamics in plasmonic systems.

Structures where both plasmonic and magnetic (spin-wave) properties can be engineered with nanoscale geometry were developed. It was found that such structures demonstrate coupling of magnetic, optical and electric effects, which can be applied in various fields ranging from optoelectronics with magnetic control to optical switching of magnetization for fast information processing.

In addition, the effects of the plasmonic environment and plasmonic excitations on various physical and chemical processes have been explored. The enhancement of the electrochromic polymer performance, faster charge transfer and a possibility to control electrochemical deposition with light and plasmonic environment have been demonstrated.