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University of Rochester
ORPA
518 Hylan Building, RC Box 270140
Rochester, NY 14627 -0140

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RPPR Final Report
as of 06-Jan-2020

Agency Code:

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INVESTIGATOR(S):

Name: Chunlei Guo
Email: guo@optics.rochester.edu
Phone Number: 5852752134
Principal: Y

Organization: **University of Rochester**
Address: ORPA, Rochester, NY 146270140
Country: USA
DUNS Number: 041294109 EIN: 160743209

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Final Report for Period Beginning 15-Jul-2015 and Ending 14-Sep-2018
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Submitted By: Chunlei Guo Email: guo@optics.rochester.edu
Phone: (585) 275-2134

STEM Degrees: 4 **STEM Participants:** 5

Major Goals: The PI's lab has developed a laser processing technique that renders highly reflective metals either totally absorptive or selectively reflective for only a certain color of light, leading to the creation of the so-called black and colored metals. The black and colored metals also possess significantly altered radiative and wetting properties and may find many Army applications, such as making better sensors, detectors, solar energy collectors, laser marking, more efficient cooling in military machinery, and improved stealth technology.
The various properties of the black and colored metals come from surface structures at micro- and nanoscales formed by the laser irradiation. However, little is known beyond this basic understanding, and the creation of the black and colored metals are mostly from trial and error.

In this project, we developed a number of techniques to monitor the dynamics of laser-induced surface structuring in order to obtain an optimal procedure to produce the functionalities associated with the black and colored metals, which includes radiative, optical, and wetting properties. Extensive research has been explored for understanding surface structure formation and the exploration of novel surface structures.

During this ARO project, a DARPA seeding project named "Infrared Signature Control" was also performed as a supplement starting from March 2017 till the end of the project. The goal of this DARPA seeding project is to produce a micro/nano-structured Ti and Al surfaces that have controlled high reflection (low emission) in air transmission bands at 1-2.5 um, 3.1-5 um, and 8-13.3 um and low reflection (high absorption) in other bands.

Accomplishments: - Developed an ultrafast microscopy technique for resolving, for the first time, the entire evolution of femtosecond laser-induced surface structural dynamics of metals. The work was published in Light: Science & Applications (a Nature Publication).
- Researched second harmonic generation (SHG) properties of nano/micro-hierarchical structures on metals fabricated by femtosecond laser ablation.
- Discovered a new type of femtosecond laser-Induced surface structures, so-called herringbone patterns on metals.
- Researched polarization dependent orientation of laser-drilled microchannels on metals.
- Researched on molecular responses to strong femtosecond laser fields.
- Researched simultaneous superhydrophobicity and color on metals.
- Developed a technique allowing us to produce periodic surface structures with controllable orientation.
- Realized real-time in situ monitoring of the structure modification dynamics by measuring the linear and nonlinear optical signals reflected from the structured surface. The collected signals in our experiments are determined by (and thus are able to reflect) the surface morphology after previous laser pulses.

- Determined that the onset of surface modification and its progress can be monitored by both the fundamental and SHG probes. However, the dynamics of laser induced periodic surface structure (LIPSS) formation can only be revealed by SHG but not fundamental because of the higher sensitivity of SHG to structural geometry.
- Researched biomimetic shark-skin structures on nickel, in which we are attempting to instill low drag, anti-fouling, and hydrophobic functionalities on metal surfaces.
- Researched superhydrophobic Al surfaces with properties of anticorrosion and reparability. The superhydrophobic surface can protect the Al from corrosion even under a very harsh environment and prolong Al in its broad usage.
- Used femtosecond laser processing to fabricate micro- and nanostructured tungsten carbide as a mold for continuous thermal imprinting of superhydrophobic surfaces. Ninety thermoplastic imprints were conducted using a single tungsten carbide mold with only minimal structural degradation.
- Researched femtosecond laser processed Ti as a mold for thermal imprinting of superhydrophobic polymer surfaces with superstrong resistance to harsh cleaning and mechanical abrasion.
- Used metal films to assist femtosecond laser fabricating two-dimensional periodic nanostructures on glass surface. Laser fabrication on glass is quite challenging particularly for two-dimensional patterning as glass doesn't absorb light readily.
- Researched multipole plasmonic metasurfaces with high transmission efficiency on controlling the propagation of visible light. By using a bilayer metallic structure, we increased the state-of-the-art efficiency by over 400%. This is work is published in Light: Science & Applications (a Nature Publication).
- Realized broadband absorption in the infrared by using multiple absorption mechanisms supported in Ti-SiO2-Al composite structure. The manuscript is prepared for submission to Optics Express (in progress).
- Used femtosecond laser pulses to fabricate periodic microholes array on a Ti film, which shows selective absorption in the infrared air transmission range.
- Researched Ge film on Ti to realize selective absorption in the air transmission near 6 um.

Training Opportunities: - Professional development, training graduate & undergraduate students under direction of Chunlei Guo (PI), Anatoliy Vorobyev (Senior Scientist), and Subhash Singh (Research Scientist)
- Hosted two undergraduate apprentices, Olivier Montmayeur and Jacob Sarvery-Verhey, under the AEOP Undergraduate Research Apprenticeship Program. The students received guidance, training, and advisement from the PI, Scientist, Postdoctoral fellows, and graduate students.
- On the invitation by the Brazilian and Peruvian Optical Society of America student chapters, the PI has visited, lectured, and interacted extensively with students from south American countries.
- The PI, students, and the postdoc attended numerous conferences:

RPPR Final Report
as of 06-Jan-2020

Results Dissemination: (A) Presentations. The research results have been broadly disseminated through talks and posters at various conferences, workshops, forums, and venues. Plenary, keynote, or invited talks have been given by the team members in the following conferences during the project period.

- 2017 Light Conference
- 2017 European Congress and Exhibition on Advanced Materials Research
- 2016 International Academy of Photonics and Laser Engineering Conference
- 2017 Forum on Applications of Laser Manufacturing
- 2017 Frontiers in Theoretical and Applied Physics meeting
- 2017 Aerotech Congress
- 2017 2nd Symposium on Optics and Lasers Applications
- 2017 22nd Microoptics Conference
- 2018 Light Conference
- 2018 12th Int'l High-Power Laser Ablation Symposium
- 2018 Int'l Conf. on Optics in Mat. Energy, and Technology
- 2018 Adv. Materials for Powerful Lasers Workshop

(B) Publications.

1. Femtosecond laser-induced periodic surface structural formation on sapphire with nanolayered gold coating
K. Yin, C. Wang, J. Duan, and C. Guo, Appl. Phys. A 122, 834(2016).
2. Photonics Products: Femtosecond Lasers - Femtosecond fiber lasers probe and process materials in new ways
S. Singh, N. Reilly, and C. Guo, Laser Focus World, August P.35 (2016).
3. Symmetry-sensitive plasmonic enhancement of nonlinear optical intensity in nano-micro hierarchical structures on silver
Y. Ogata, A. Y. Vorobyev, and C. Guo, Surface & Interface Analysis 48, 1108 (2016).
4. Polarization and molecular-orbital dependence of strong field enhanced ionization
W. Lai and C. Guo, Phys. Rev. A 93, 043401 (2016).
5. The role of molecular electron distribution in strong-field ionization and dissociation of heteronuclear molecules
W. Lai and C. Guo, J. of Phys. B 49, 225601 (2016).
6. Ranran Fang, Anatoliy Y. Vorobyev, and Chunlei Guo, "Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals," Light: Science & Applications 6, e16256 (2017).
7. Yoichi Ogata and Chunlei Guo, "Nonlinear Optics on Nano/Micro Hierarchical Structures on Metals: Focus on Symmetric and Plasmonic Effects," Nano Review & Exp. 8, 1339545 (2017).
8. Current-voltage characteristics influenced by nanochannel diameter and surface charge density in a fluidic field-effect-transistor
K.P. Singh and C. Guo, Physical Chemistry Chemical Physics 19, 15701 (2017).
9. Lam, Billy, Jihua Zhang, and Chunlei Guo. "Generation of continuously rotating polarization by combining cross-polarizations and its application in surface structuring." Optics Letters 42 2870-2873 (2017).
10. Jihua Zhang, Yizhuo He, Billy Lam, and Chunlei Guo, "Real-time in situ study of femtosecond-laser-induced periodic structures on metals by linear and nonlinear optics," Opt. Express 25, 20323-20331 (2017).
11. Zhibing Zhan, Zihao Li, Zhi Yu, Subhash Singh, and Chunlei Guo, "Superhydrophobic Al Surfaces with Properties of Anticorrosion and Reparability," ACS Omega 3, 17425-17429 (2018).
12. Ranran Fang, Anatoliy Y. Vorobyev, Subhash Singh, and Chunlei Guo, "Ultrafast microscopy in resolving femtosecond laser-induced surface structuring," Jap. J. Appl. Phys. 57, 8S2 (2018).
13. Erik M. Garcell, Billy Lam, and Chunlei Guo, "Femtosecond Laser-Induced Herringbone Patterns," Appl. Phys. A 124, 405 (2018).
14. Erik M. Garcell, and Chunlei Guo, "Polarization-Controlled Microchannel Arrays Induced by Femtosecond Laser Pulses," J. Appl. Phys. 123, 213103 (2018).
15. Erik M. Garcell, and Chunlei Guo, "Colorful multifunctional surfaces produced by femtosecond laser pulses," Opt. Mat. Express 9, 1033 (2019).
16. Zhibing Zhan, Erik M Garcell, and Chunlei Guo, "Robust mold fabricated by femtosecond laser pulses for continuous thermal imprinting of superhydrophobic surfaces," Mater. Res. Express 6, 075011 (2019).
17. Zhibing Zhan, Zihao Li, Xiaoyun Li, Erik Garcell, Subhash Singh, Mohamed ElKabbash, and Chunlei Guo, "Creating Superhydrophobic Polymer Surfaces with Superstrong Resistance to Harsh Cleaning and Mechanical Abrasion Fabricated by Scalable One-Step Thermal-Imprinting," Adv. Mater. Interfaces, 1900240 (2019).
18. Yizhuo He, Jihua Zhang, Subhash Sing, Erik Garcell, Anatoliy Y. Vorobyev, Billy Lam, Zhibing Zhan, Jianjun Yang, and Chunlei Guo, "Maskless laser nano-lithography of glass through sequential activation of multi-threshold ablation," Appl. Phys. Lett. 114, 133107 (2019).
19. Jihua Zhang, Mohamed ElKabbash, Ran Wei, Subhash C. Singh, Billy Lam and Chunlei Guo, "Plasmonic

metasurfaces with 42.3% transmission efficiency in the visible," Light: Science & Applications 8, 53 (2019).

(C) Media outreach
The PI's research has been broadly disseminated through popular media outlets including major newpapers, major Radio interview, TED talk, and TV documentary and programs. The following are some examples
• Spanish popular TV Talk show El Hormiguero Appearance (Nov. 21, 2018).
• FOX Channel Documentary: Xploration 2050 (2016).
• Science Friday Radio Interview aired on NPR (Jan. 23, 2015)
• ABC News (Jan. 23, 2015): "Behold a Material So Water Repellent That Liquid Just Bounces Off".
• USA Today (Jan. 20, 2015): "Scientists make metal surfaces water-repellent".
• CNN (Jan. 20, 2015): "Laser-transformed metal so slick that water bounces off".
• BBC (Jan. 21, 2015): "Laser-etched metal 'bounces' water".

Honors and Awards: - 2017 Light Conference Best Poster Presentation Award for "Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals"
- T.C. Graham Prize, Association for Iron & Steel Technology, 2017
- GE-Statoil Innovation Challenge Award, GE-Statoil, 2016
- Excellent Overseas Design Award in Sanitation and Toilet Renovation, The Gates Foundation & Chinese Tourism Administration, 2016
- Popular Science-National Science Foundation visualization challenge award finalist, 2016.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Faculty
Participant: Anatoliy Vorobyev
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Jihua Zhang
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Chunlei Guo
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Yizhuo He
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Erik Garcell
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Erik Garcell
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Billy Lam
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Chun-Hao Fann
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Olivier Montmayeur
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
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Participant Type: Undergraduate Student
Participant: Jacob Sarvery-Verhey
Person Months Worked: 3.00 **Funding Support:**
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Publication Location:
Article Title: Femtosecond laser one-step direct-writing cylindrical microlens array on fused silica
Authors: Z. Luo, J. Duan, and C. Guo
Keywords: femtosecond laser processing
Abstract: We demonstrate an efficient method for fabricating high-quality cylindrical microlens arrays (CMLAs) on the surface of fused silica, fully based on spatially shaping of a femtosecond laser beam from Gaussian to Bessel distribution. As the envelope of shaped spatial intensity distribution matches the profile of cylindrical microlens perfectly, a CMLA with more than 50 uniform microlenses is fabricated by simple line scanning. The radius and height of these microlens units can be finely controlled by adjusting the power of laser pulses. Excellent optical imaging and high-speed fabrication performances are also demonstrated by our fabricated CLMA.
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Volume: 114 Issue: 13 First Page #: 133107
Date Submitted: Date Published: 4/1/19 12:00AM
Publication Location: rochester, ny, usa
Article Title: Maskless laser nano-lithography of glass through sequential activation of multi-threshold ablation
Authors: Yizhuo He, Jihua Zhang, Subhash Singh, Erik Garcell, Anatoliy Y. Vorobyev, Billy Lam, Zhibing Zhan, Ji
Keywords: Maskless, laser nano-lithography
Abstract: Controllable nanofabrication is at the very foundation of nano-science and nano-technology. Today, ultrafast laser writing has been broadly adopted for micro-fabrication because of its ability to make precise and rapid processing of almost all types of materials in an ambient environment. However, direct laser writing is typically unsuitable for high-quality 2D nano-patterning. In this work, we introduce a maskless laser nano-lithographic technique that allows us to create regular 2D periodic nanopatterns on glass. Glass is a particularly challenging material since it does not absorb light readily. Our strategy starts with a glass sample being coated with a thin layer of metal, and then irradiated with a series of pulse bursts at progressively increasing fluence levels. This process allows us to sequentially activate a series of tailored physical processes that lead to the formation of regular 2D periodic nanopatterns on glass.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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WEBSITES:

URL: https://www.sciencedaily.com/releases/2017/03/170314150941.htm
Date Received: 30-Aug-2017
Title: Science Daily coverage of our work
Description: this is a news coverage of our paper entitled: 29. Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals
URL: https://www.eurekalert.org/pub_releases/2017-03/uor-iat031417.php
Date Received: 30-Aug-2017
Title: News coverage of our work by EurakAlert!
Description: This is a news coverage on our paper entitled: 29. Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals
URL: http://www.physnews.com/nano-physics-news/cluster1671531753/
Date Received: 30-Aug-2017
Title: News coverage on Physics News
Description: this is a news covrage of our paper entitled: 29. Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals

Nothing additional to report in the uploaded pdf

(see accomplishments and the rest of the materials provided)