

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 09-08-2021		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Jul-2020 - 31-Mar-2021	
4. TITLE AND SUBTITLE Final Report: Optical imaging of ultrafast photo-induced phase transitions of nanostructures using neural lenses			5a. CONTRACT NUMBER W911NF-20-1-0256		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Rochester ORPA 518 Hylan Building, RC Box 270140 Rochester, NY 14627 -0140			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 76872-MS-II.5		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Chunlei Guo
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 585-275-2134

RPPR Final Report

as of 19-Aug-2021

Agency Code: 21XD

Proposal Number: 76872MSII

Agreement Number: W911NF-20-1-0256

INVESTIGATOR(S):

Name: Ph.D. Chunlei Guo
Email: chunlei.guo@rochester.edu
Phone Number: 5852752134
Principal: Y

Organization: **University of Rochester**

Address: ORPA, Rochester, NY 146270140

Country: USA

DUNS Number: 041294109

EIN: 160743209

Report Date: 30-Jun-2021

Date Received: 09-Aug-2021

Final Report for Period Beginning 01-Jul-2020 and Ending 31-Mar-2021

Title: Optical imaging of ultrafast photo-induced phase transitions of nanostructures using neural lenses

Begin Performance Period: 01-Jul-2020

End Performance Period: 31-Mar-2021

Report Term: 0-Other

Submitted By: Ph.D. Chunlei Guo

Email: chunlei.guo@rochester.edu

Phone: (585) 275-2134

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3

STEM Participants: 2

Major Goals: Under this Short-Term Innovative Research (STIR) Project, we have made a range of progresses on our project on Machine Learning for dynamic surface structural reconstruction. Our main goal was to demonstrate machine learning's ability to recover images from optical degradation. We used Neural Networks (NNs) to apply image super-resolution to the images obtained using ultrafast time-resolved scattered-light microscopy techniques.

Accomplishments: The ultrafast time-resolved scattered-light microscopy system utilizes scattered-light to obtain near-zero background and high-contrast images of the surface structural evolution due to laser ablation. However, because of the coherent illumination of the laser beam, any ablation structures on the scattered-light image will induce speckle patterns, making the ablation structures hard to be recognized. Therefore, we have modified the experimental setup to reduce the speckle noise, and have developed a Generative Adversarial Networks (GAN) to further suppress the speckle noise.

A GAN contains two sub-networks: the generator network that we train to generate new images and the discriminator network that tries to classify the generated images as either real or fake. The two networks are trained together in an adversarial way until the generator network can generate plausible images. We used a combination of multiple loss functions to evaluate the performance of the generator network to simulate the perceptual judgment of human eyes. The implemented natural feature extractor [1] has been found to deliver the final quality better than other types of metrics (such as mean square error or structure similarity index).

The coherent light source always causes speckles. Generally, the speckle noise can be reduced by superimposing many speckle patterns that look differently and obtain these patterns' average [2]. According to Goodman [3], if N independent speckle patterns with equal mean intensity are averaged, the speckle will be reduced by $1/N^{1/2}$. Thus, we placed a static diffuser into the probe beam light path to reduce the speckle noise. The diffuser introduces a spatially random optical path length (OPL) to the beam. Since the light source is from a broadband femtosecond laser. The same OPL would give a different phase towards light with different wavelengths. And the speckles for different wavelength light would be formed in different location. Therefore, speckles formed by different wavelength would be averaged, and the speckle noise would be reduced to some extent.

To further reduce the speckle noise, we developed a GAN to suppress the speckle noise. Generally, a moving diffuser can reduce the speckle noise to a relatively low level. The light source becomes incoherent at a relatively long exposure time as the diffuser moves. However, taking multiple images and obtaining the average is not realistic in ultrafast imaging because the pulse duration is so short that only one image can be taken. We trained our GAN to suppress the speckle noise from a single speckle image to solve this problem. We generated the network training dataset by taking multiple speckle images toward the same target. The diffuser was mounted on a

RPPR Final Report as of 19-Aug-2021

translation stage, moving at a constant speed. The speckle patterns changed as the diffuser moved, and the constant moving speed ensured that every speckle image was different from others. The single-frame speckle images were used as training data, the average of those images was used as the training label, and the GAN was trained to transfer the data to its corresponding label. To ensure the reliability of the training label, we developed an image registration algorithm, which is used to align the images with overlapping, to reduce the vibration noise when calculating the average. The algorithm used the low-frequency information of the grids (intentionally made for image alignment for alignment, ignoring the high-frequency speckle noise and resulting in reliable ground truth speckle-averaged images.

Training Opportunities: A PhD student and an undergraduate students have worked on this project. A number of other postdoctoral fellows and students also participated discussions and gained experience in machine learning. The undergraduate student has gained a significant amount of research experience through this project and has been admitted into our PhD program as a new phd student.

Results Dissemination: The PI has worked with ARO on some research dissemination during the project. One example is that we worked with the PM and the ARO press office to disseminate our research in applying our laser treated surfaces for water purification. The research has been broadly disseminated by over 40 media outlets with an Almetric score of 414. One article on the Army website is linked below,

https://www.army.mil/article/237210/new_solar_material_could_clean_drinking_water

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: one provisional patent was filed during the project on developing Fano resonant optical coatings.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Chunlei Guo

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Cong Cong

Person Months Worked: 4.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student

Participant: Tianshu Xu

Person Months Worked: 3.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Billy Lam

Person Months Worked: 1.00

Project Contribution:

Funding Support:

RPPR Final Report

as of 19-Aug-2021

National Academy Member: N

ARTICLES:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Sustainability

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41893-020-0566-x

Volume: 3 Issue: 11

First Page #: 938

Date Submitted: 8/9/21 12:00AM

Date Published: 7/1/20 12:00PM

Publication Location:

Article Title: Solar-trackable super-wicking black metal panel for photothermal water sanitation

Authors: Subhash C. Singh, Mohamed ElKabbash, Zilong Li, Xiaohan Li, Bhabesh Regmi, Matthew Madsen, Soh

Keywords: femtosecond, lasers, surface patterning, water purification

Abstract: Optical coatings are integral components of virtually every optical instrument. However, despite being a century-old technology, there are only a handful of optical coating types. Here, we introduce a type of optical coatings that exhibit photonic Fano resonance, or a Fano-resonant optical coating (FROC). We expand the coupled mechanical oscillator description of Fano resonance to thin-film nanocavities. Using FROCs with thicknesses in the order of 300 nm, we experimentally obtained narrowband reflection akin to low-index-contrast dielectric Bragg mirrors and achieved control over the reflection iridescence. We observed that semi-transparent FROCs can transmit and reflect the same colour as a beam splitter filter, a property that cannot be realized through conventional optical coatings. Finally, FROCs can spectrally and spatially separate the thermal and photovoltaic bands of the solar spectrum, presenting a possible solution to the dispatchability problem in photovoltaics.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Nanotechnology

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41565-020-00841-9

Volume: 16 Issue: 4

First Page #: 440

Date Submitted: 8/9/21 12:00AM

Date Published: 2/1/21 5:00AM

Publication Location:

Article Title: Fano-resonant ultrathin film optical coatings

Authors: Mohamed ElKabbash, Theodore Letsou, Sohail A. Jalil, Nathaniel Hoffman, Jihua Zhang, James Rutledge

Keywords: optical coating, optics, lasers

Abstract: Optical coatings are integral components of virtually every optical instrument. However, despite being a century-old technology, there are only a handful of optical coating types. Here, we introduce a type of optical coatings that exhibit photonic Fano resonance, or a Fano-resonant optical coating (FROC). We expand the coupled mechanical oscillator description of Fano resonance to thin-film nanocavities. Using FROCs with thicknesses in the order of 300 nm, we experimentally obtained narrowband reflection akin to low-index-contrast dielectric Bragg mirrors and achieved control over the reflection iridescence. We observed that semi-transparent FROCs can transmit and reflect the same colour as a beam splitter filter, a property that cannot be realized through conventional optical coatings. Finally, FROCs can spectrally and spatially separate the thermal and photovoltaic bands of the solar spectrum, presenting a possible solution to the dispatchability problem in photovoltaics.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report as of 19-Aug-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1364/OL.432800
Volume: 46 **Issue:** 16 **First Page #:** 3901
Date Submitted: 8/9/21 12:00AM **Date Published:** 8/1/21 4:00AM
Publication Location:
Article Title: Compact vectorial optical field generator using a single phase-only spatial light modulator
Authors: Billy Lam, Chunlei Guo
Keywords: optical fields
Abstract: In this study, we demonstrate a compact vectorial optical field generator for any coherent light, including femtosecond laser beams. The apparatus utilizes a single Köster prism for both beam splitting and recombining. A phase-only spatial light modulator is used as a diffractive optical element to encode the two complex fields that recombine after being converted to orthogonal polarizations, generating an arbitrary vectorial optical field. We apply this setup to shape focused femtosecond pulses in producing patterned structures.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1364/OL.417997
Volume: 46 **Issue:** 8 **First Page #:** 1796
Date Submitted: 8/9/21 12:00AM **Date Published:** 4/1/21 4:00AM
Publication Location:
Article Title: Spectrally resolved wedged reversal shearing interferometer
Authors: Billy Lam, Chunlei Guo
Keywords: optical field
Abstract: In this study, we demonstrate a compact vectorial optical field generator for any coherent light, including femtosecond laser beams. The apparatus utilizes a single Köster prism for both beam splitting and recombining. A phase-only spatial light modulator is used as a diffractive optical element to encode the two complex fields that recombine after being converted to orthogonal polarizations, generating an arbitrary vectorial optical field. We apply this setup to shape focused femtosecond pulses in producing patterned structures.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: Y

Partners

,

RPPR Final Report
as of 19-Aug-2021

I certify that the information in the report is complete and accurate:

Signature: chunlei guo

Signature Date: 8/9/21 4:41AM

STIR Project Report

Optical imaging of ultrafast structural dynamics using neural lenses

Chunlei Guo
The Institute of Optics, University of Rochester

Under this Short-Term Innovative Research (STIR) Project, we have made a range of progresses on our project on Machine Learning for dynamic surface structural reconstruction. Our main goal was to demonstrate machine learning's ability to recover images from optical degradation. We used Neural Networks (NNs) to apply image super-resolution to the images obtained using ultrafast time-resolved scattered-light microscopy techniques (UTRM).

The ultrafast time-resolved scattered-light microscopy system utilizes scattered-light to obtain near-zero background and high-contrast images of the surface structural evolution due to laser ablation. However, because of the coherent illumination of the laser beam, any ablation structures on the scattered-light image will induce speckle patterns, making the ablation structures hard to be recognized. Therefore, we have modified the experimental setup to reduce the speckle noise, and have developed a Generative Adversarial Networks (GAN) to further suppress the speckle noise.

A GAN contains two sub-networks: the generator network that we train to generate new images and the discriminator network that tries to classify the generated images as either real or fake. The two networks are trained together in an adversarial way until the generator network can generate plausible images. We used a combination of multiple loss functions to evaluate the performance of the generator network to simulate the perceptual judgment of human eyes. The implemented natural feature extractor [1] has been found to deliver the final quality better than other types of metrics (such as mean square error or structure similarity index).

The coherent light source always causes speckles. Generally, the speckle noise can be reduced by superimposing many speckle patterns that look differently and obtain these patterns' average [2]. According to Goodman [3], if N independent speckle patterns with equal mean intensity are averaged, the speckle will be reduced by $1 / \sqrt{N}$. Thus, we placed a static diffuser into the probe beam light path to reduce the speckle noise. The diffuser introduces a spatially random optical path length (OPL) to the beam. Since the light source is from a broadband femtosecond laser. The same OPL would give a different phase towards light with different wavelengths. And the speckles for different wavelength light would be formed in different location. Therefore, speckles formed by different wavelength would be averaged, and the speckle noise would be reduced to some extent.

To further reduce the speckle noise, we developed a GAN to suppress the speckle noise. Generally, a moving diffuser can reduce the speckle noise to a relatively low level. The light source becomes incoherent at a relatively long exposure time as the diffuser moves. However, taking multiple images and obtaining the average is not realistic in ultrafast imaging because the pulse duration is so short that only one image can be taken. We trained our GAN to suppress the speckle noise from a single speckle image to solve this problem. We generated the network training dataset by taking multiple speckle images toward the same target. The diffuser was mounted on a translation stage, moving at a constant speed. The speckle patterns changed as the diffuser moved,

and the constant moving speed ensured that every speckle image was different from others. The single-frame speckle images were used as training data, the average of those images was used as the training label, and the GAN was trained to transfer the data to its corresponding label. To ensure the reliability of the training label, we developed an image registration algorithm, which is used to align the images with overlapping, to reduce the vibration noise when calculating the average. The algorithm used the low-frequency information of the grids (intentionally made for image alignment, as shown in Fig. 1a) for alignment, ignoring the high-frequency speckle noise and resulting in reliable ground truth speckle-averaged images.

We have successfully applied GAN-based speckle suppression to a static laser ablation target. As shown in Fig. 1, the speckle pattern in the GAN predicted speckle-averaged image is smoothed, and the ablation structure is more pronounced. But the speckle patterns still exist in the GAN predicted speckle-averaged image, which might be caused by imperfection of the training labels.

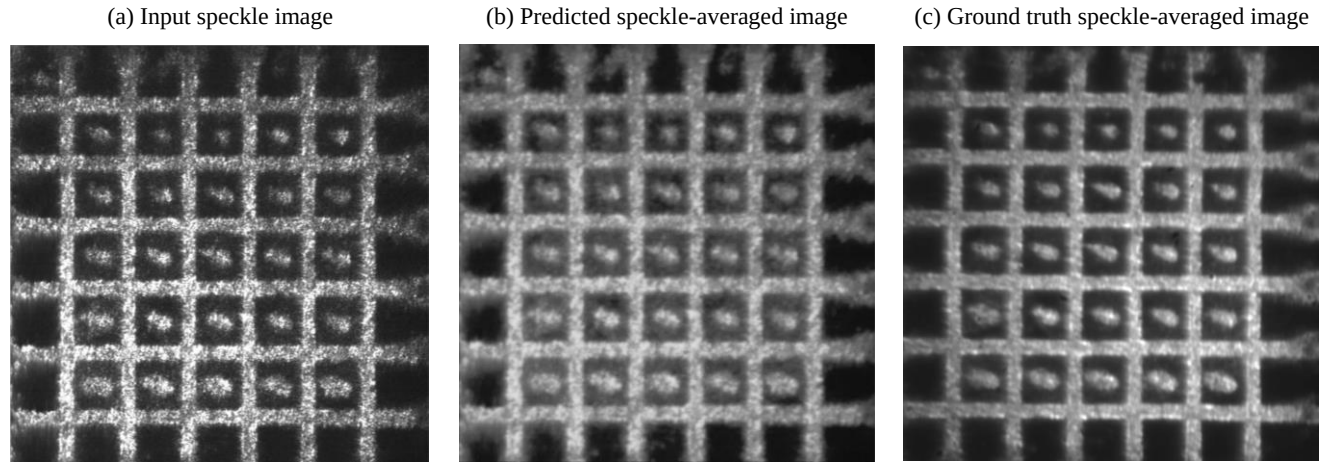


Fig. 1. GAN-based speckle suppression of the static laser ablation sample. (a) Input experimental speckle image; (b) predicted speckle-averaged image from GAN; (c) Ground truth speckle-averaged image, which is the average of 110 single speckle images.

To further improve the GAN prediction results, we developed a speckle simulation algorithm to generate the speckle image of given geometric structures. Fig. 2 shows the simulated speckle image and its ground truth speckle-averaged image. The intensity of the simulated image was adjusted to match the experimental images. The simulated speckle images were used as training data, and the average of several speckle images was used as the training label. Without experimental errors, the simulated images could lead to better GAN prediction results. A large dataset with different levels of speckle-noise was then generated using the speckle simulation algorithm. Fig. 3 shows the GAN prediction results using different training datasets. We can see that GAN trained with simulated images (Fig. 3b) shares high similarity with the ground truth speckle-averaged image (Fig. 3c), and it shows a clear outline of the ablation structure and less speckle-noise.

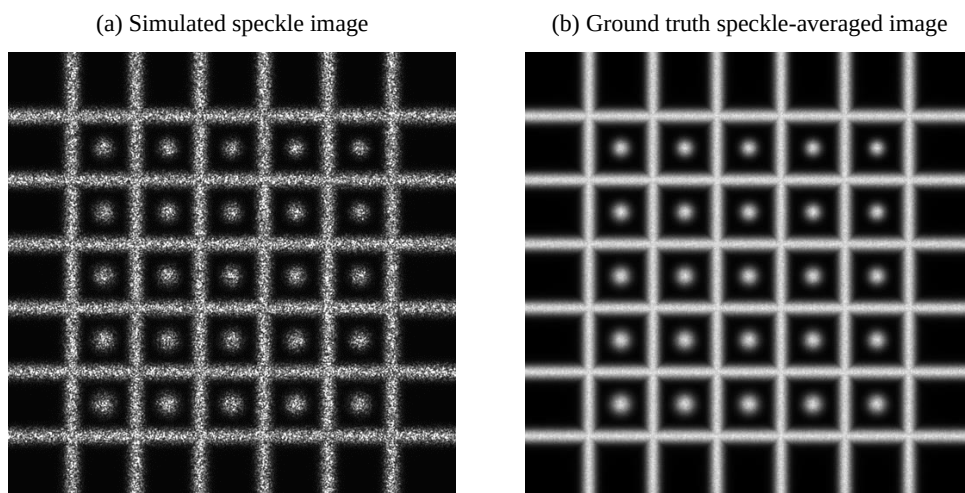


Fig. 2. (a) Simulated speckle image. (b) Ground truth speckle-averaged image, which is the average of several simulated speckle images.

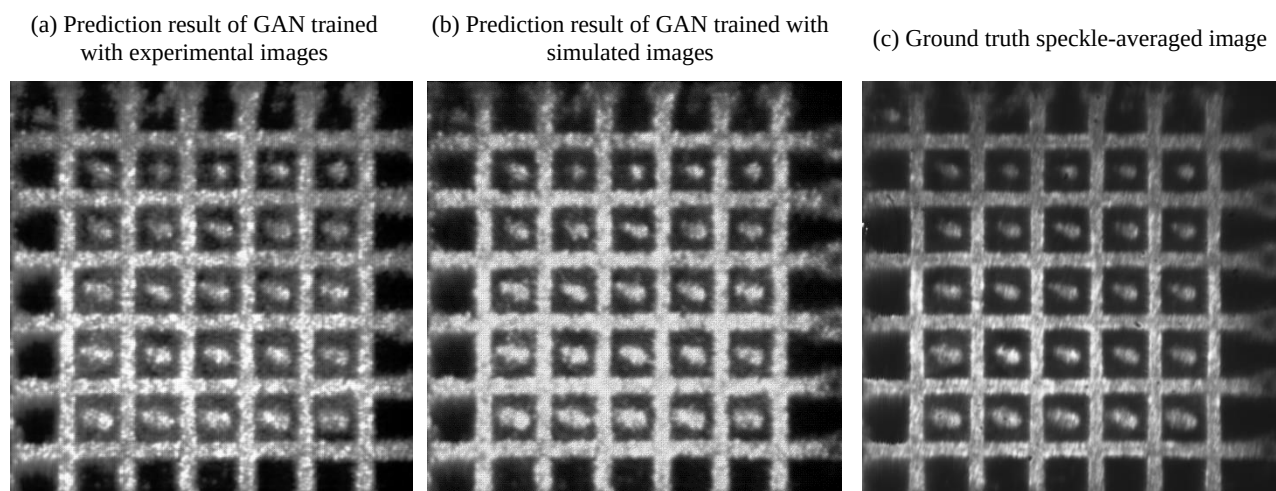


Fig. 3. GAN prediction results using different training datasets. (a) Prediction result of GAN trained with experimental images; (b) Prediction result of GAN trained with simulated images; (c) Ground truth speckle-averaged image, which is the average of 110 single speckle images.

To measure the amount of speckle noise present, we can calculate the speckle index of the image [4], which is defined as

$$\frac{1}{(N-2)^2} \sum_{m,n=2}^{N-1} \frac{\sigma(m,n)}{\mu(m,n)}$$

where m and n represent the pixel location on the image; $\sigma(m, n)$ and $\mu(m, n)$ are local deviation and local mean, of the 3 by 3 area centered at (m, n) ; N is the total number of pixels in each column and row. The lower the value of the speckle index, the less speckle noise presents in the image. Fig. 4 shows the speckle indices of the input speckle image, the predicted speckle-averaged image from GAN trained with different datasets, and the Ground truth speckle-averaged image obtained from 110 single speckle images. For the GAN trained with experimental images, the speckle index of the GAN's prediction result decreases about 47% compared with the input speckle image. For the GAN trained with simulated images, the speckle index decreased about 62% compared with the input speckle image. This result demonstrates the capability of our GAN to suppress the speckle noise from a single speckle image.

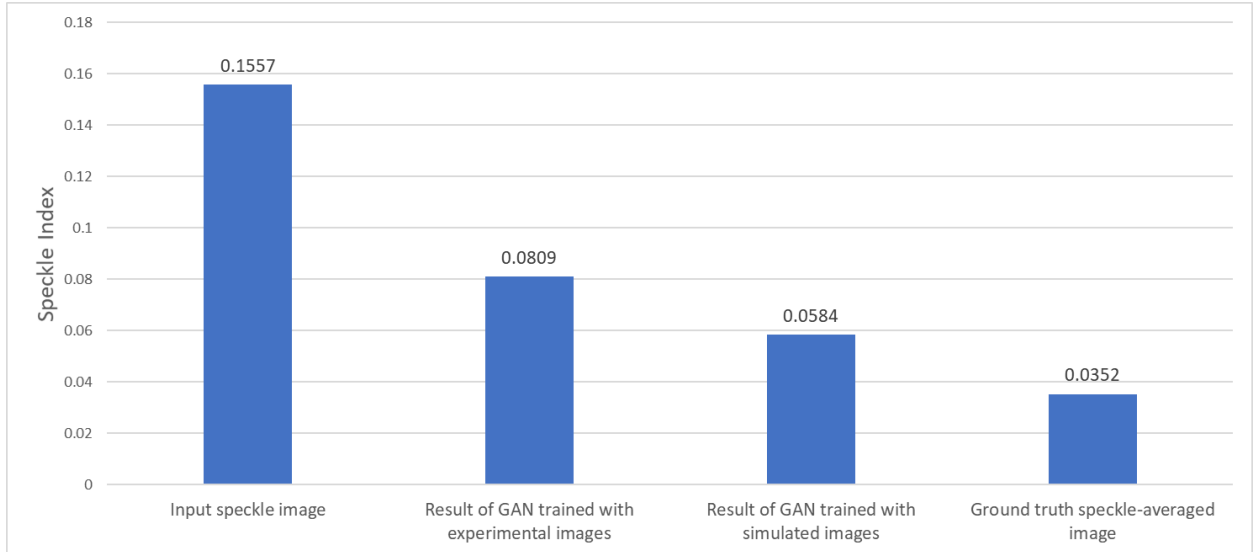


Fig. 4. Average speckle indices of the input speckle image, the predicted speckle-averaged image from GAN trained with different datasets, and the ground truth speckle-averaged image.

Our project's final goal is to reconstruct surface structural patterns through machine learning at different time delays from the time-resolved images obtained using scattered light. We found that the speckle noise in the scattered light image limited the ultrafast time-resolved scattered-light microscopy ability to resolve ablation structures. At this stage, we have successfully applied GAN-based speckle suppression to a single speckle image. Our GAN can decrease the speckle index by half from a single speckle image and greatly enhanced image quality, allowing us to recognize detailed ablation structures buried in the speckle noise. For the next step, we plan to perform the complete ultrafast time-resolved scattered-light microscopy experiment to resolve the transient surface structure formation due to laser ablation.

References

1. J. Johnson, A. Alahi, L. Fei-Fei Perceptual losses for real-time style transfer and super-resolution In: ECCV. (2016)
2. Akram M N, Chen X. Speckle reduction methods in laser-based picture projectors[J]. Optical Review, 2016, 23(1): 108-120.
3. Goodman, J.W.: Speckle phenomenon in optics: theory and applications. Roberts and Company, Greenwood Village (2007)
4. Crimmins, T. R. (1985). Geometric filter for speckle reduction. Applied optics, 24(10), 1438-1443.