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as of 19-Aug-2021

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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

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 signficant 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 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Tianshu Xu
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Billy Lam
Person Months Worked: 1.00 **Funding Support:**
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Date Submitted: 8/9/21 12:00AM Date Published: 7/1/20 12:00PM
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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.
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Article Title: Fano-resonant ultrathin film optical coatings
Authors: Mohamed ElKabbash, Theodore Letsou, Sohail A. Jalil, Nathaniel Hoffman, Jihua Zhang, James Rutled
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.
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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.
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Acknowledged Federal Support: **Y**

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Volume: 46 Issue: 8 First Page #: 1796
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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

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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.

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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.

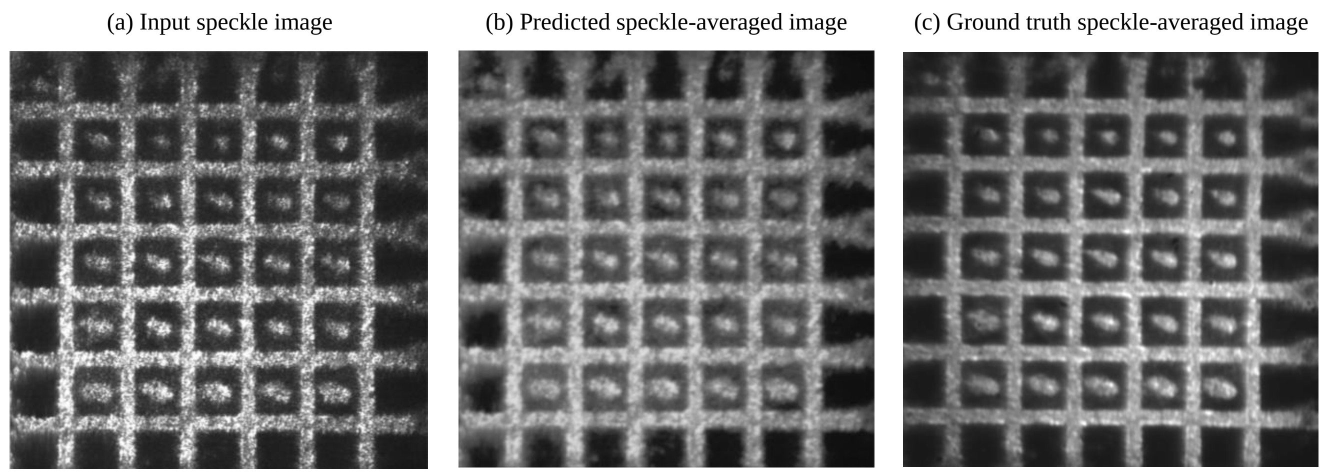

Fig. 1. GAN-based speckle suppression of the static laser ablation sample. (a) Input experimental speckle image; (b) predicted speckle-averaged image from GAN; (c) Ground truth speckle-averaged image, which is the average of 110 single speckle images.

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.

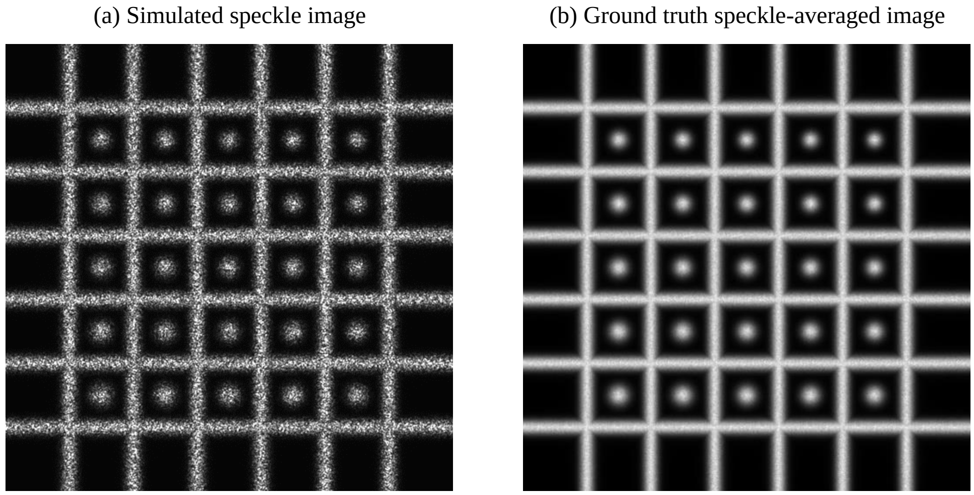

Fig. 2. (a) Simulated speckle image. (b) Ground truth speckle-averaged image, which is the average of several simulated speckle images.

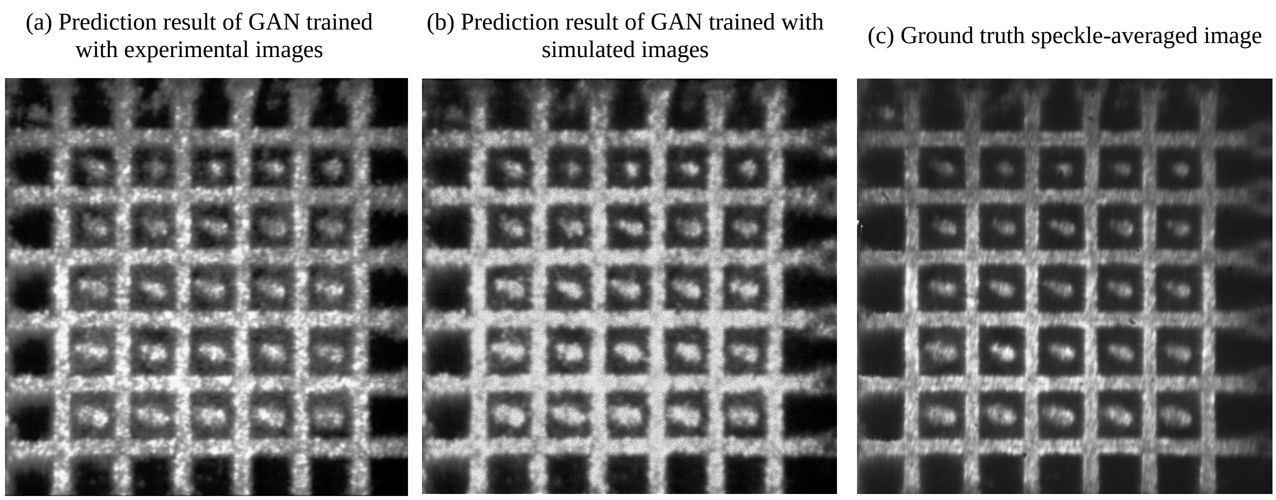

Fig. 3. GAN prediction results using different training datasets. (a) Prediction result of GAN trained with experimental images; (b) Prediction result of GAN trained with simulated images; (c) Ground truth speckle-averaged image, which is the average of 110 single speckle images.

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.

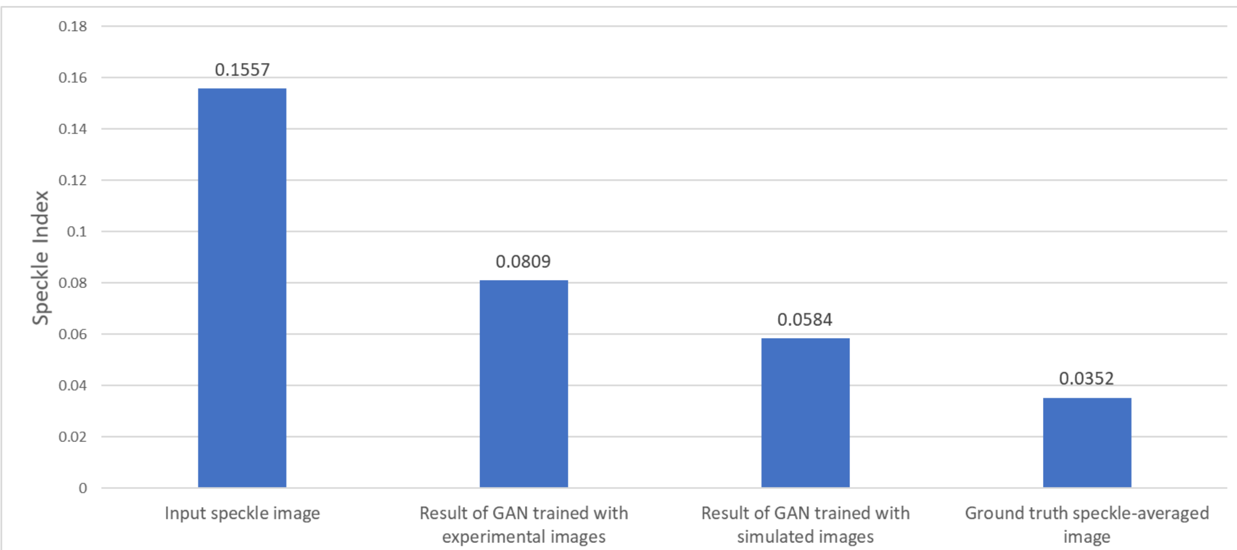

Fig. 4. Average speckle indices of the input speckle image, the predicted speckle-averaged image from GAN trained with different datasets, and the ground truth speckle-averaged image.

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.