Imaging of weak-contrast objects beyond shot noise limit

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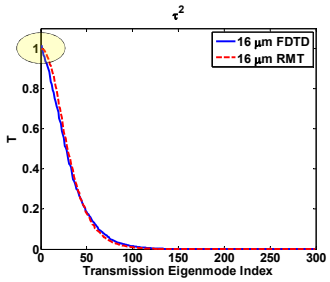
Introduction

Eigenchannels differentiates objects depending on their absorptivity

- Random matrix theory predicts perfect reflection
- Singular value decomposition of the backscattering matrix

$$t = U \tau V^{\dagger}$$

V : Unitary matrix connecting input waves into eigenchannels
U : Unitary matrix connecting eigenchannels into output channels
τ : Real non-negative diagonal matrix



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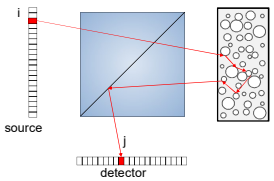
Choi, W. et al. *Phys. Rev. B* **83**, 134207 (2011).

- Each eigenchannel takes proper spatial distribution depending on the absorptivity distribution of the scattering medium

Materials and method

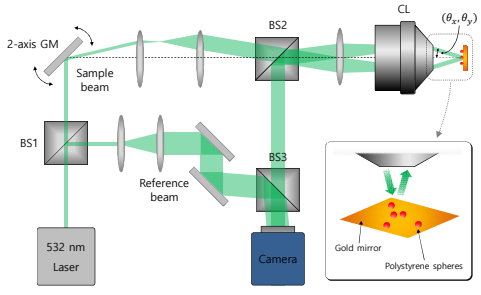
Definition of backscattering matrix



$$E_j^{(out)} = \sum_i r_{ji} E_i^{(in)}$$

$$\vec{E}^{(out)} = r\vec{E}^{(in)}$$

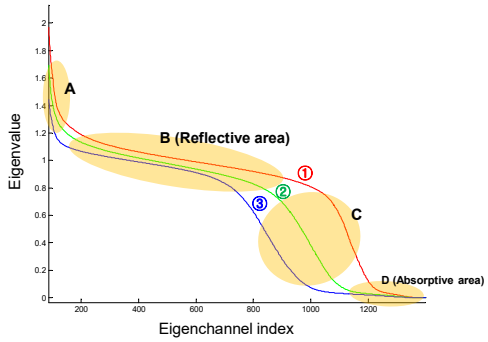
Experimental setup

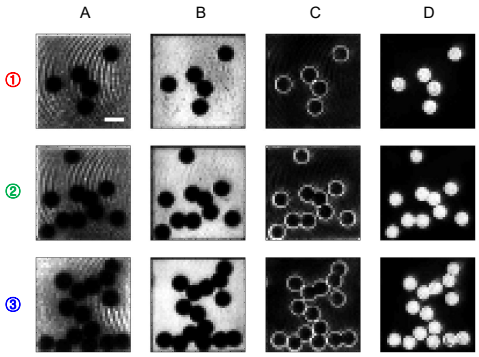


- 532 nm pulse laser
- Scattering medium: Mixture of PDMS and ZnO powder
- Imaging target: Red polystyrene sphere (diameter 6 ㎛)
- Experimental condition
  - Illumination area: 21.6 x 21.6 ㎛
  - Illumination NA: 0.6
  - Recording NA: 0.6
  - Recorded image: 2000

Results

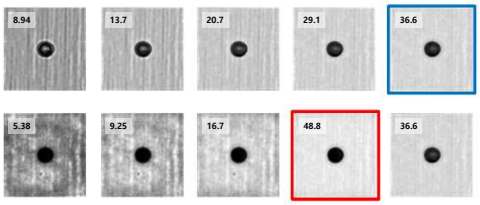
Absorptive area on reflective mirror surface





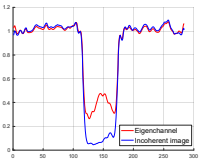
- From the eigenvalue curve, reflective area (B) and absorptive area can be identified
- We could selectively image the area with specific absorptivity, by selectively summing the eigenchannel images identified from the eigenvalue curve
- Scale bar 3 um

Accumulation of eigenchannel images



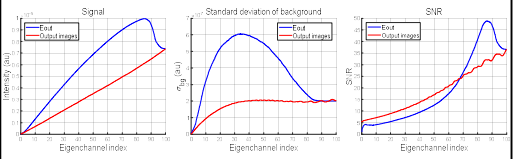
- Figure above shows incoherently summed images using plane wave output images and eigenchannel output images
- Plane wave illuminates uniformly on imaging target and mirror surface, while eigenchannel selectively illuminates each surface on their reflectivity.
- By selectively summing the open eigenchnnel, which is reflected on the mirror, SNR of absorptive target enhanced by 36.6 → 48.8

Contrast enhancement using eigenchannel images



- Compared to conventional incoherent summed image, the SNR of selectively summed eigenchannel image improved by ~50 %

SNR analysis



- The accumulative intensity image was analyzed with their signal, standard deviation of background, and SNR (signal to noise ratio)
- The signal curve of eigenchannel images has maximum peak, while the curve of plane wave output images increases linearly
- Because the final standard deviation of background of each method is same, the SNR of eigechannel image has bigger value than conventional incoherent sum
- In that case, the SNR of eigenchannel image enhanced by ~33 %

Conclusion

- We recorded a reflection matrix of a absorptive imaging target on mirror surface
- We identified reflection eigenchannels of the scattering medium
- Eigenchannels identified from the singular value decomposition of the backscattering matrix differentiated objects depending on their absorptivity
- By using the property, we improved the imaging contrast and SNR of absorptive objects in comparison with the conventional incoherent illumination imaging
- Contrast enhanced by ~50 % and SNR enhanced by ~33 %
- This work show that this approach has a potential to detect an extremely small spatial variation of absorbance beyond the traditional detection limit dictated by shot noise

Reference

[1] Moonseok Kim, Youngwoon Choi, Changhyeong Yoon, Wonjun Choi, Jaisoon Kim, Q-Han Park and Wonshik Choi, "Maximal energy transport through disordered media with the implementation of transmission eigenchannels," Nature Photonics, 6 581 (2012)

[2] Moonseok Kim, Wonjun Choi, Changhyeong Yoon, Guang Hoon Kim, Seunghyun Kim, Gi-Ra Yi, Q-Han Park, and Wonshik Choi, "Exploring anti-reflection modes in disordered media," Optics express, 23, 12740-12749 (6 May 2015)

[3] Wonjun Choi, Allard P. Mosk, Q-Han Park and Wonshik Choi, "Transmission eigenchannels in a disordered medium," Physical Review B 83, 134207 (2011)