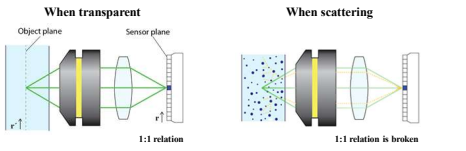
Space gating for multiple scattering suppression: a step toward deep-tissue phase imaging

Hakseok Ko[1,2], Mooseok Jang[1,2*], Jae-Seung Lee[3], Wonshik Choi[1*]

[1]Center for Molecular Spectroscopy and Dynamics, Institute for Basic Science (IBS), 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea.
[2]Department of Physics, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea.
[3]Department of Materials Science and Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
*Correspondence to: majng@korea.ac.kr (M.J.), wonshik@korea.ac.kr (W.C.)

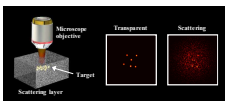
Introduction

Multiple scattering breaks the 1:1 relation between sensor and object planes



✓ **Through transparent medium**
A sensor element gets **ballistic signals** only

✓ **Through scattering medium**
A sensor element gets
ballistic signals + **multiply scattered components**
(Information) *(Noise)*

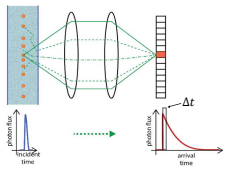


✓ Ballistic signal component ∝ $\exp(-L/l_s)$
✓ Noise component ∝ $1/L$

→ Results in imaging depth limit through a scattering medium

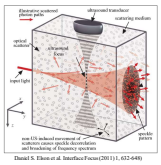
Other methods to image inside scattering media

✓ **Suppressing multiple scattering noises – Time gating**



- Relies on the early-arriving property of ballistic photons
- For the refection measurement, arriving time is not related to the depth of target

✓ **Exploiting multiple scattering - UOT (Ultrasound-modulated optical tomography)**



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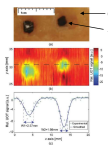

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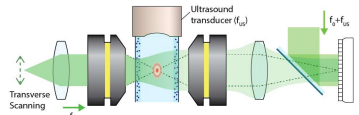
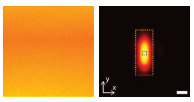
- Imaging depth ~cm
- Imaging resolution is restricted by ultrasound wavelength ~μm
- Photoacoustic tomography, diffuse optical tomography

Demonstration of space gating imaging

Validation of space gating

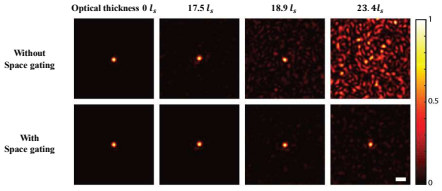




✓ Left: Conventional bright field imaging
✓ Right: Space gated imaging using acousto-optic effect

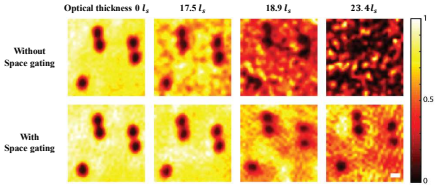
- Selectively measuring the ultrasonically-modulated light, we could implement the space gating method
- Scale bar: 30 μm

Point spread functions through scattering media



- Scale bar: 5 μm

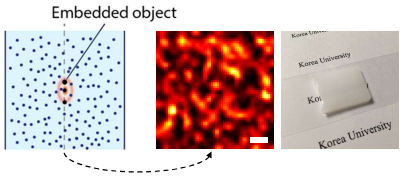
Demonstration of optical resolution imaging of 2 μm gold beads



- Images are measured and reconstructed by scanning 900 points within a field of view of 32.5 μm
- Each image is normalized by its maximum intensity
- Scale bar: 2 μm

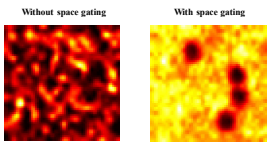
Space gating imaging on embedded target

Schematic of the imaging configuration

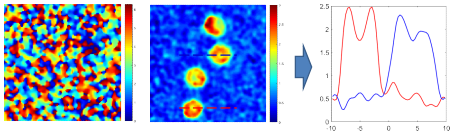


✓ We prepared PAA gel layers containing 0.8 % of fat emersion (intralipid)
✓ The optical thickness of the scattering slab was ~ 20 l_s
✓ Fully developed speckle pattern was measured at the object plane after removing the right -hand side of the scattering medium shows (scalebar: 1 μm)
✓ the speckle grain size was 300 nm in width, about half the wavelength

Amplitute target, 2 μm gold beads



Phase target, red blood cells

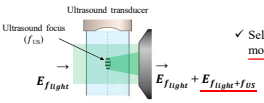


Conclusion

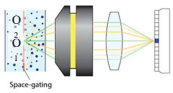
- We selectively recorded ultrasonically modulated light by placing ultrasound focus on the object plane
- We could image inside a ultrasound focused area, with optical resolution 1.5 μm
- By using spatial gating method with the focused ultrasound, we could suppressed multiple scattering noise by more than 100 times
- We demonstrated ideal diffraction-limited imaging of fully embedded objects within a scattering medium whose thickness is larger than 20 l_s
- As a novel and independent gating complimentary to the conventional gating methods, the space gating will help us to reach the ultimate imaging depth set by the dynamic range limit of detecting ballistic waves.

Concept of space gating

Concept



✓ Selectively measuring of ultrasonically modulated light enables the space-gating

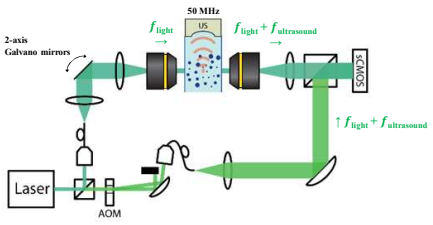


✓ Multiple scattering component
— Ungated (from O_1)
··· Gated (from O_2) → **"Blocked"**

✓ Noise suppression ratio

$$\eta_{SG} \sim \frac{\text{(photon flux through space-gating window } O_1\text{)}}{\text{(total photon flux)}}$$

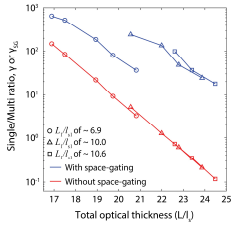
Experimental scheme



✓ 532 nm DPSS ns pulse laser
✓ Space-gating implemented using acousto-optic effect
✓ Frequency-modulated (50 MHz) component selectively detected interferometerically
✓ # of incidence basis : 900

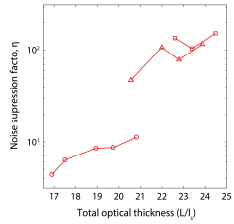
Effect of space gating depending on the optical thicknesses

Ratio of ballistic to multiply scattered waves



- Ratio of ballistic to multiply scattered waves with (τ_{SG}, **blue**) and without space gating (τ, **red**) as a function of the total optical thickness
- The optical thicknesses of the input and output layers are varied for each case

Noise suppression ratio of space gating



- Multiply scattered wave reduced by **more than 100 times** by space gating

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