Time-gated iterative phase conjugation of reflected wave

Dong-Young Kim, Seungwon Jeong, Ye-Ryoung Lee, and Wonshik Choi

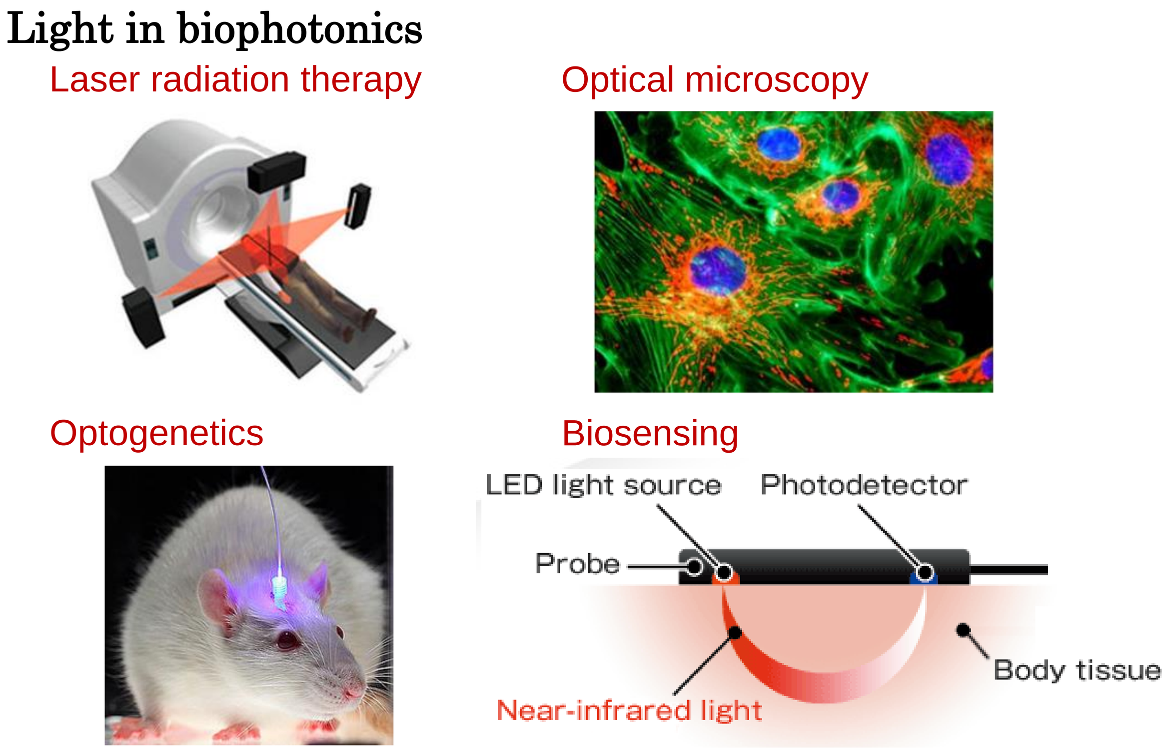
Center for Molecular Spectroscopy and Dynamics, Institute for Basic Science (IBS), Seoul 02841, Republic of Korea
Department of Physics, Korea University, Seoul 02841, Korea

Abstract

In the field of optical imaging and therapy, where light is used to diagnose or treat disease, it is important to deliver sufficient light energy to a target within the biological tissues. However, the tissues give rise to multiple light scattering and spatial spread of the propagating waves as they are complex media composed of structures with various refractive indices. For this reason, the light energy delivered to a target object is steeply decreased with the increase of depth. Here, we propose an iterative phase conjugation of the time-gated backscattered waves to enhance the efficiency of light energy delivery. Since the proposed method is much faster than the previous methods, it will facilitate the transfer of techniques to the in vivo applications.

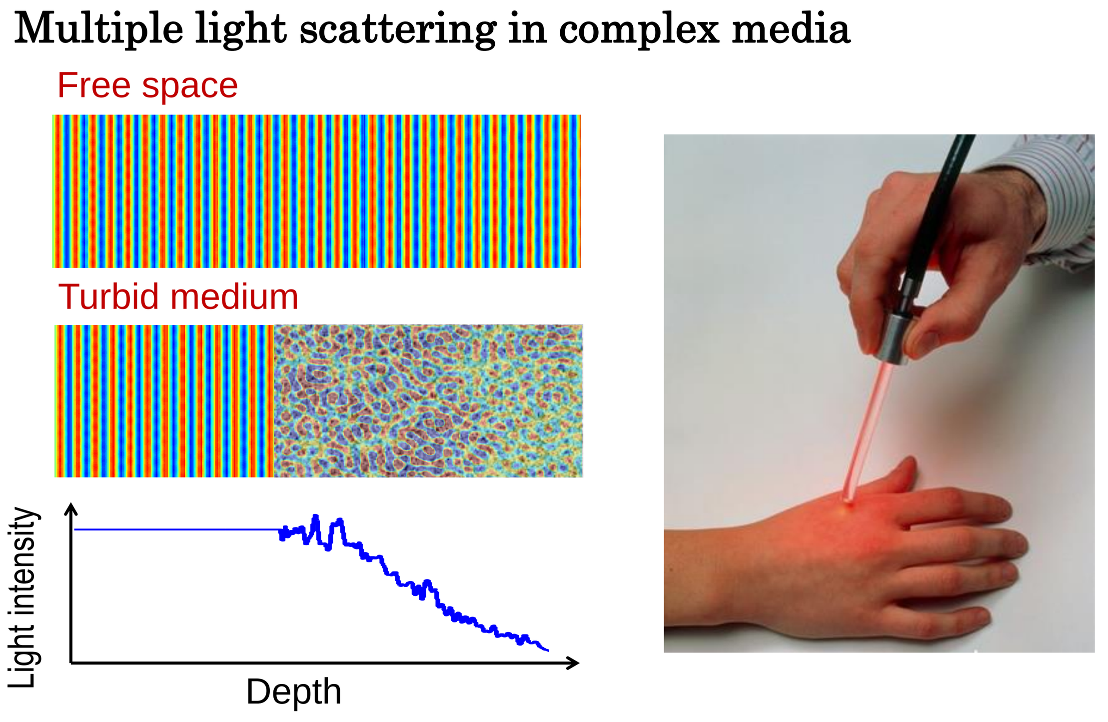
Motivation

Light in biophotonics



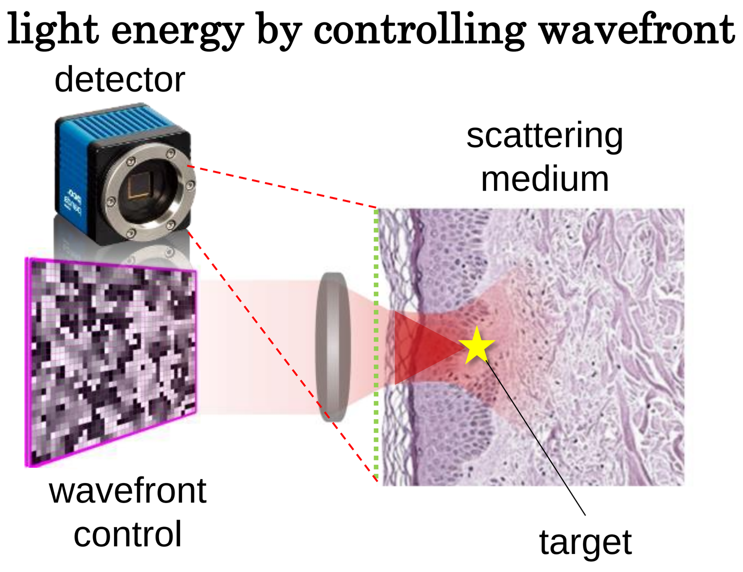
- ✓ Light is widely used in bio-medical application.
- ✓ If light goes deep under the skin tissue, these approaches are undermined due to tissue turbidity.

Multiple light scattering in complex media



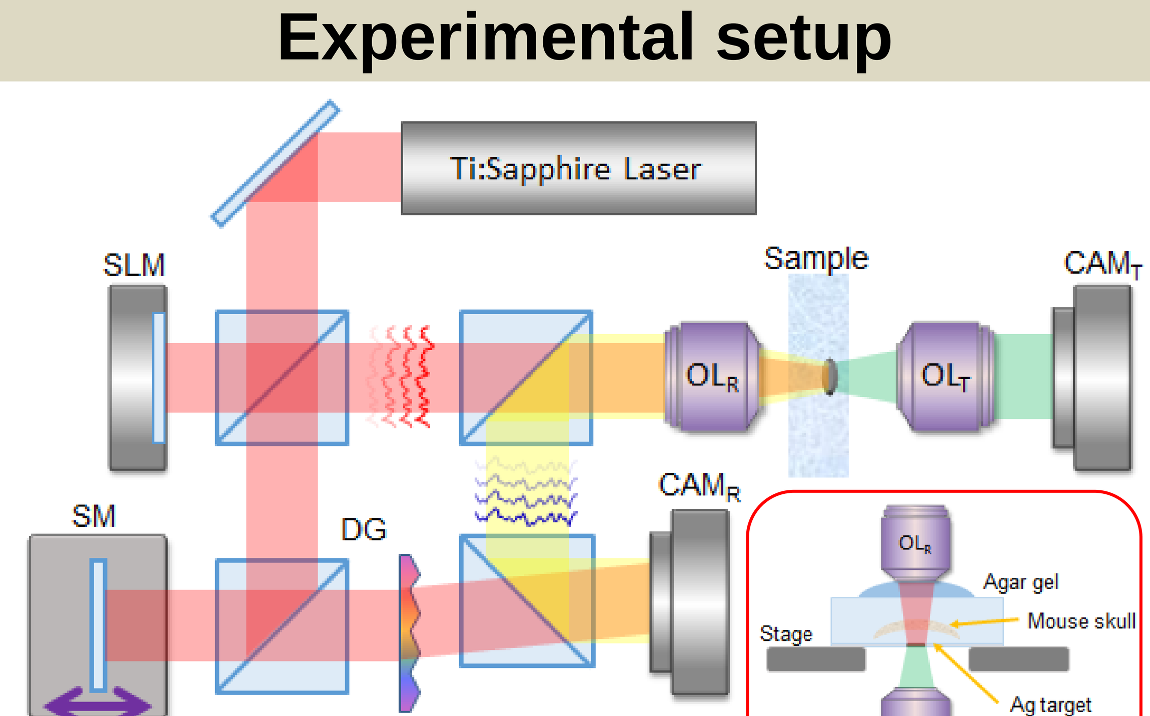
- ✓ Light wave is randomly diffused by scattering medium, and its energy is linearly attenuated.
- ✓ Fundamental limitation to *in vivo* sensing and control.

Focusing light energy by controlling wavefront



- ✓ Our goal is focusing light energy to the target within the scattering medium by sending waves with proper wavefront.

Experimental setup

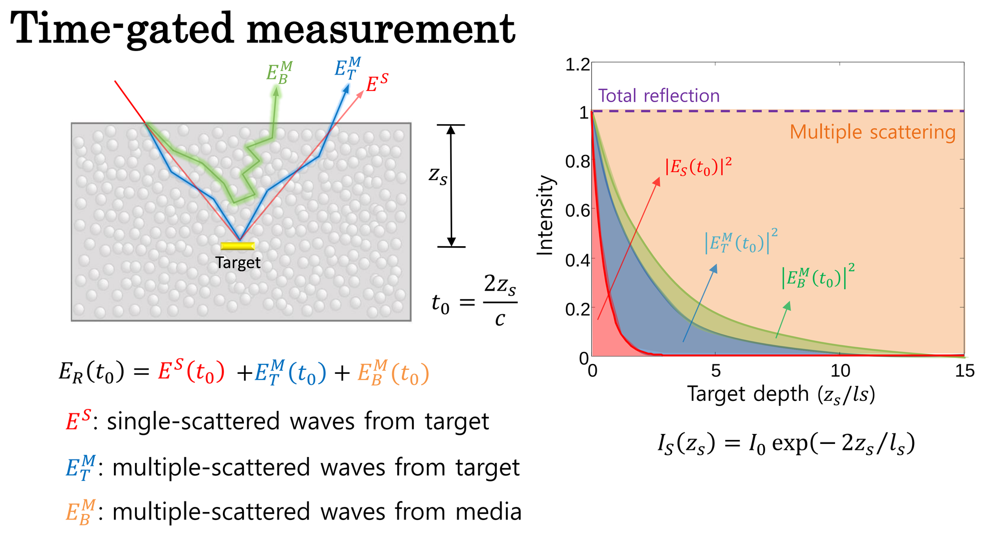


OL : Objective lens, DG : Diffraction grating, SM : Scanning mirror
SLM : Spatial light modulator, Ti:S : $\lambda_0 = 780\ nm$, $\Delta\lambda = 10\ nm$

- ✓ Time-gated detection using low coherence light source.
- ✓ Wide-field detection by off-axis interferometry.
- ✓ Wavefront shaping to control the incident angle.
- ✓ We placed 9-days mouse skull embedded in agar gel on the 10 μm silver disk target.
- ✓ We measured backscattered field at the target flight time. Then, conjugated reflection phase was sent back to the sample iteratively.

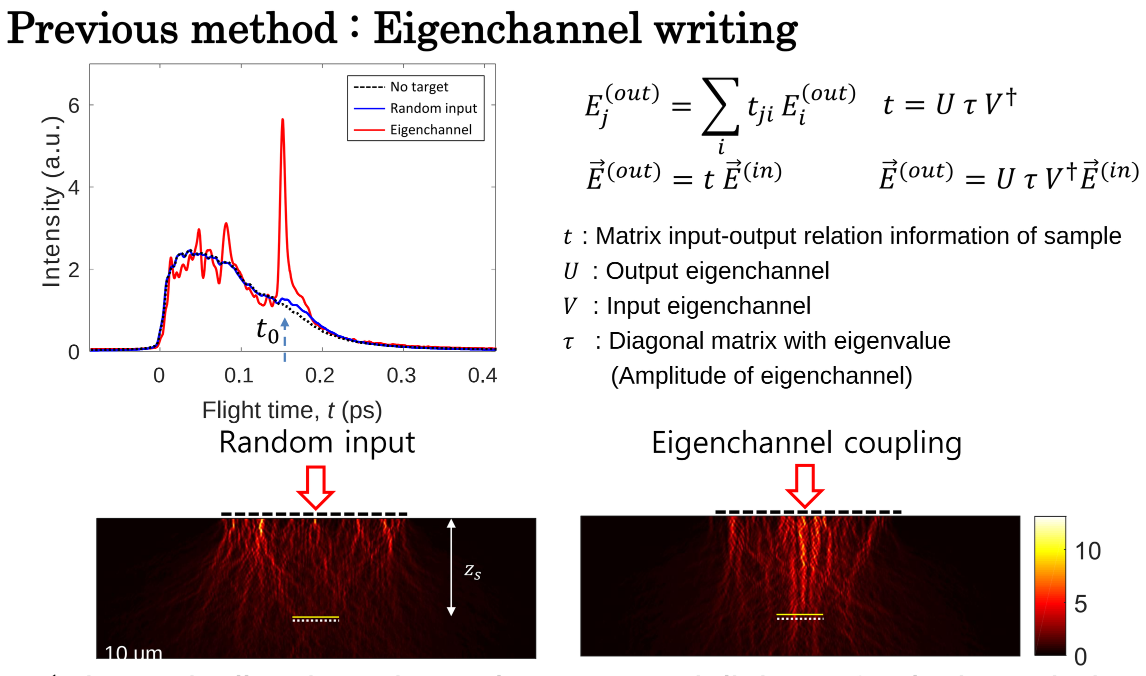
Methods

Time-gated measurement



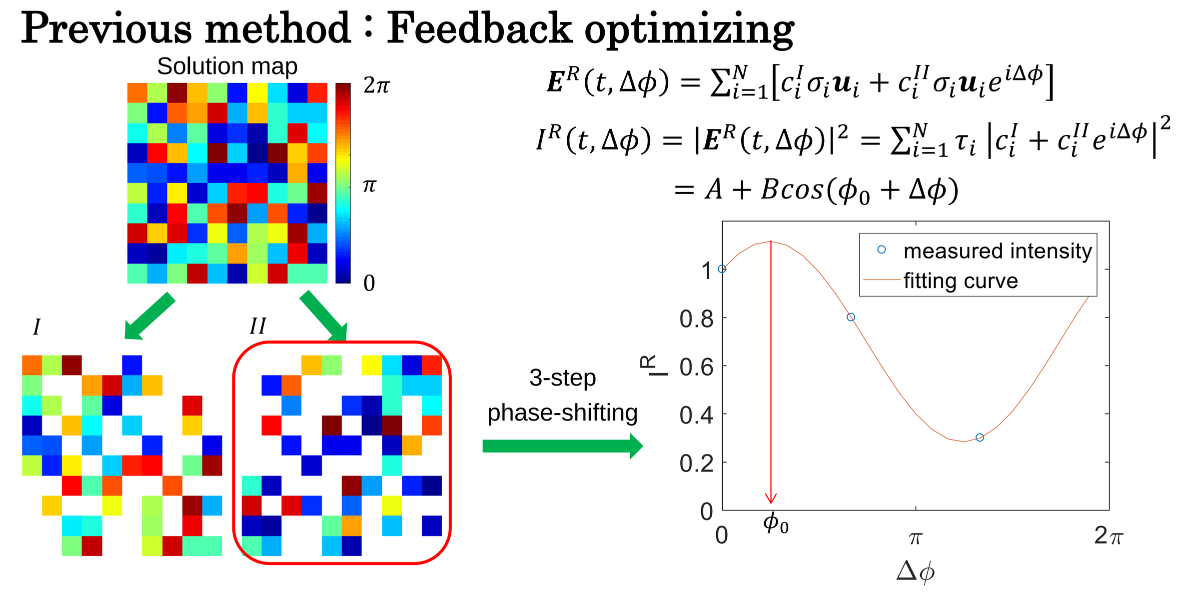
- ✓ Time-gating can remove the multiple-scattered waves $E_R(t \neq t_0)$.
- ✓ There are 3 types of backscattered wave detected at $t = t_0$.
- ✓ For the case of deeply embedded target, most of time-gated signal is multiple-scattered waves. ($|E_B^M| > |E_T^M|$)

Previous method : Eigenchannel writing



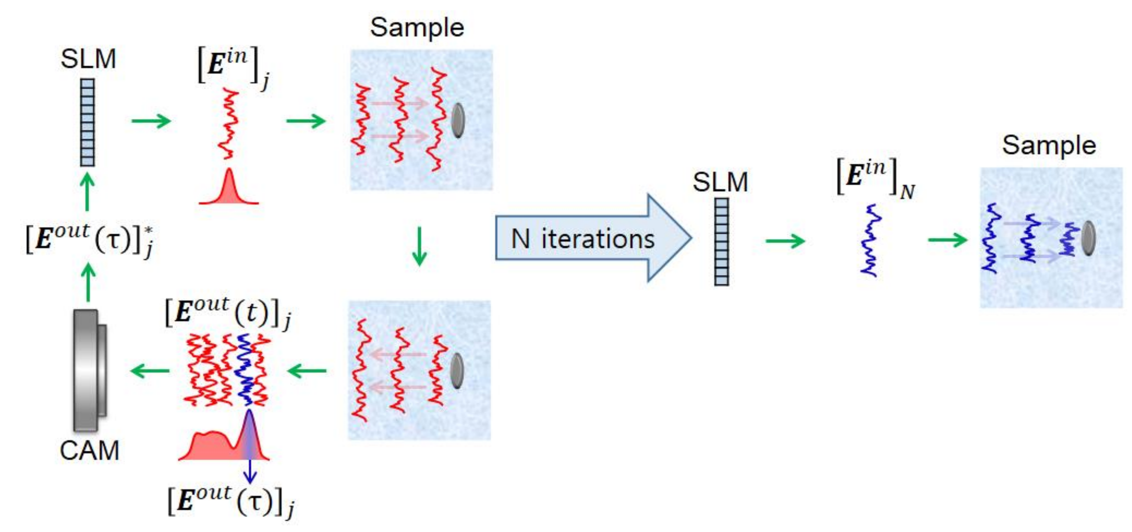
- ✓ Theoretically, eigenchannel can transmit light perfectly through the scattering medium by wavefront control.
- ✓ Light energy delivered to target is enhanced with time-gated reflection eigenchannel.
- ✓ This method should measure the matrix that characterizes the objects, which needs stable condition when measuring the matrix.

Previous method : Feedback optimizing



- ✓ Incident wave is decomposed into parts I and II, and the phase of second parts s shifted by $\Delta\phi$.
- ✓ We find ϕ_0 that maximizes the time-gated reflection signal for each iteration steps by 3-step phase-shifting interferometry.
- ✓ Total intensity of time-gated reflection increases with the successive iteration of the maximization process.
- ✓ This method should measure thousands of images to reach maximum intensity.

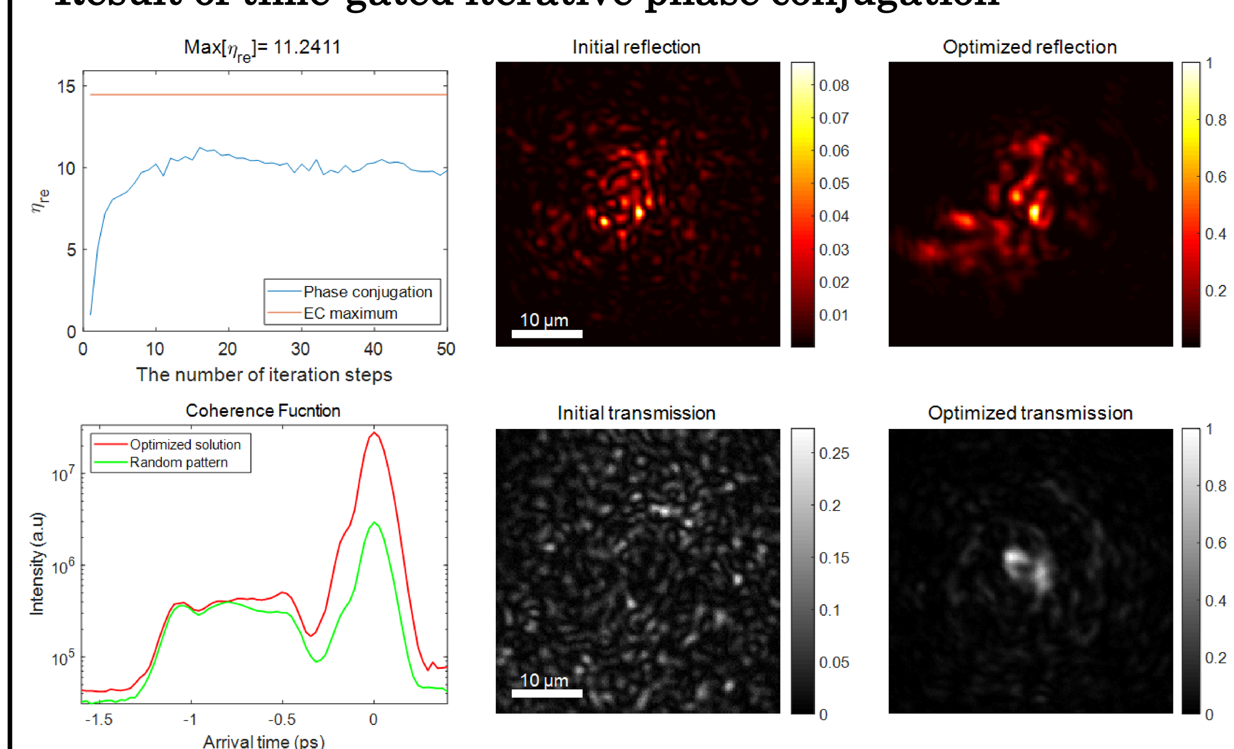
Iterative phase conjugation of time-gated reflection wave



- ✓ We measured backscattered field at the target flight time.
- ✓ Conjugated reflection phase was sent back to sample.
- ✓ By repeating this process iteratively, we found the pattern that can enhance light energy delivered to the target object.
- ✓ Measurement was much faster than previous methods.
- ✓ The pattern changed adaptively to the vibrations or movements of the sample.

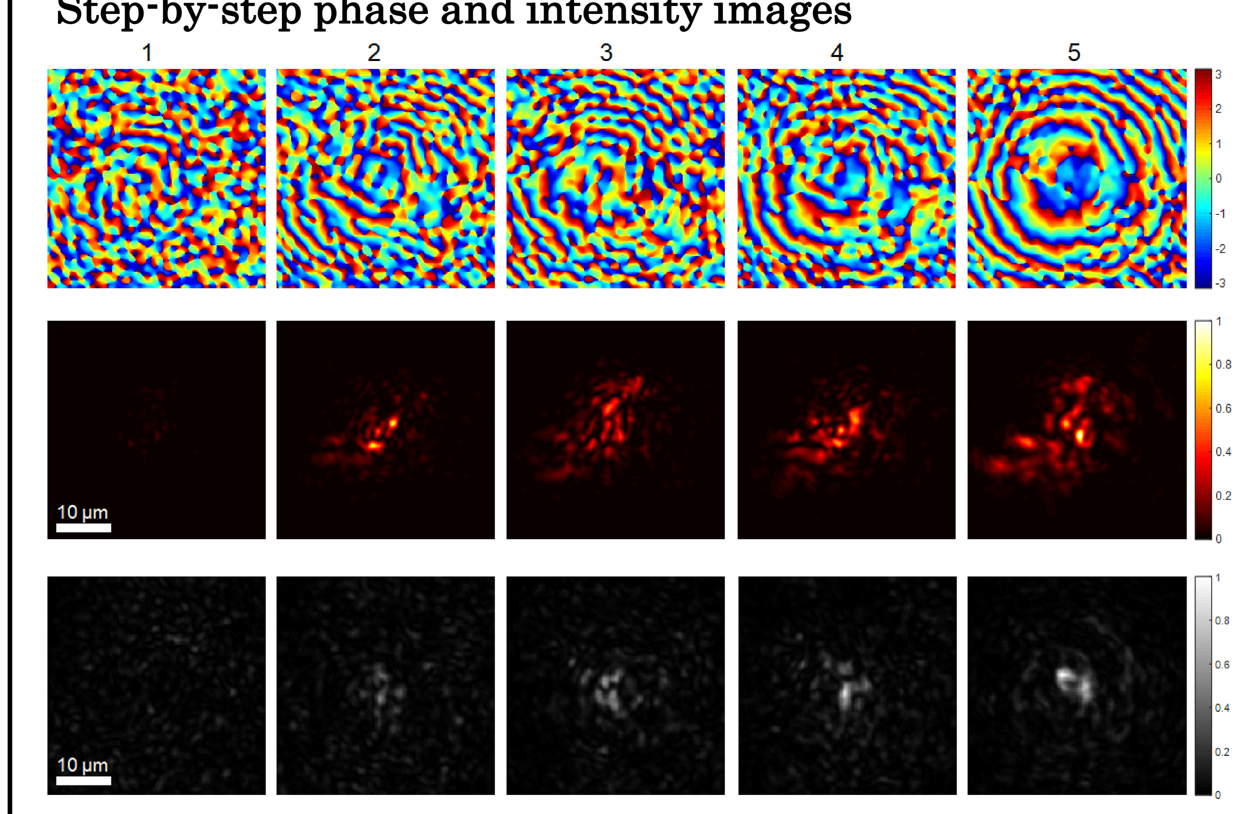
Experimental result

Result of time-gated iterative phase conjugation

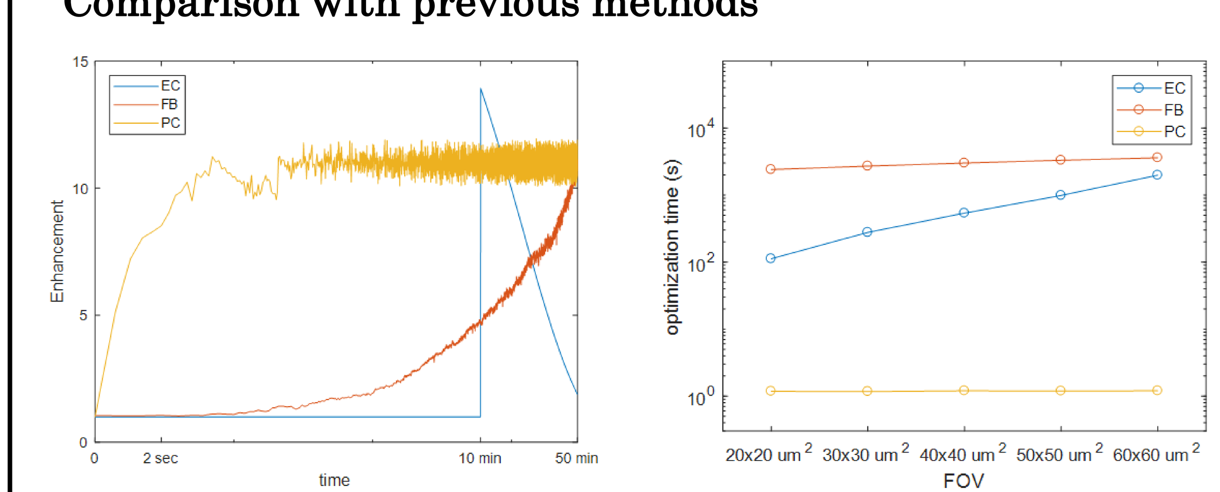


- ✓ With increase of the number of iterations, time-gated reflection intensity is optimized.
- ✓ Enhancement of time-gated reflection η_{re} is nearly close to time-gated eigenchannels.
- ✓ We measured the reflection temporal response by controlling the length of reference arm.
- ✓ Optimized solution enhances the intensity of only target area when time-gating was setting to flight time of target depth.

Step-by-step phase and intensity images



Comparison with previous methods



- ✓ Our proposed method reached maximum enhancement in a few seconds while previous methods took several tens of minutes.
- ✓ In phase conjugation approach, the reflection enhancement conserved during iterations after 2 seconds.
- ✓ Optimization time was almost independent to the size of view field while measurement and computation time of the eigenchannel method increased exponentially.

Summary

- ✓ By combining time-gated detection and iterative phase conjugation, we could control the signal of the specific flight time that is reflected from scattering media.
- ✓ We could demonstrate target-specific light energy delivery from reflection and transmission images.
- ✓ We confirmed that the measurement time was shortened by hundreds times compared with previous methods.
- ✓ Since the pattern was updated at each step, the pattern changed adaptively to the vibrations or movements of the sample.
- ✓ We expected that our proposed method useful for real-time optical imaging or therapy.

ibs 기초과학연구원 Institute for Basic Science
고려대학교 KOREA UNIVERSITY
CMSD Center for Molecular Spectroscopy and Dynamics, IBS-Korea University