Feedback of time-gated reflection signals for enhancement of light energy delivery to the deeply embedded target

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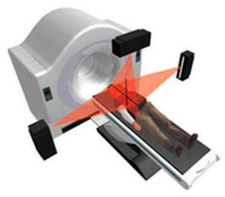
Abstract

The efficiency of light energy delivery to the target object embedded in the scattering medium such as biological tissues is crucial for biomedical imaging, optogenetics and phototherapy. However, due to the multiple light scattering in the complex medium, the light waves get diffused in both space and time, and only a small fraction of the incident light can be delivered to the target object. As a consequence, optical methodologies have been effective only to the shallow layers, and their effect decreases with depth of the target object. Here, we present time-gated reflection feedback method to enhance light energy delivered to the target object by the iterative optimization of time-gated multiple light waves scattered from the target object. The proposed method can overcome the sample perturbation such as mechanical drift, while the previous time-gated matrix approach is susceptible to any perturbation.

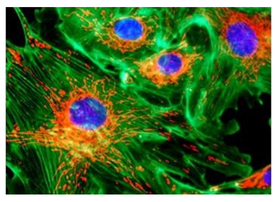
Motivation

Light in biophotonics

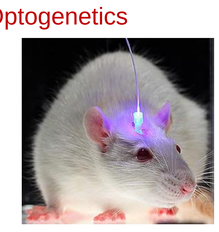
Laser radiation therapy



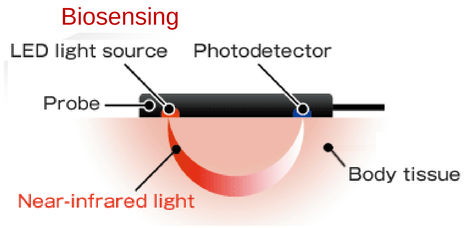
Optical microscopy



Optogenetics



Biosensing

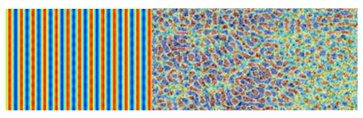


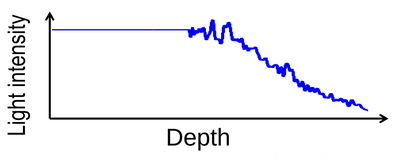
- ✓ Light is widely used in bio-medical application.
- ✓ If light goes deep under the skin tissue, these approaches are undermined due to tissue turbidity.

Multiple light scattering in complex media

Free space

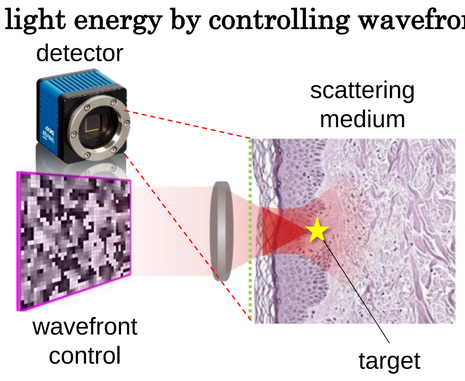
Turbid medium





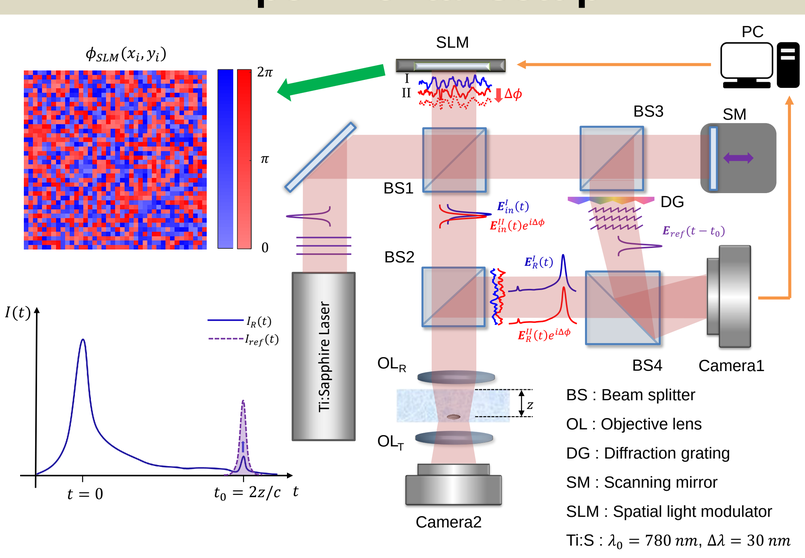
- ✓ Light wave is randomly diffused by scattering medium, and its energy is linearly attenuated.
- ✓ Fundamental limitation to *in vivo* sensing and control.

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

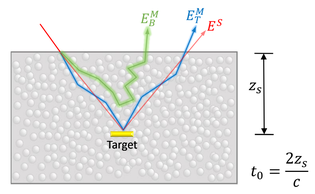


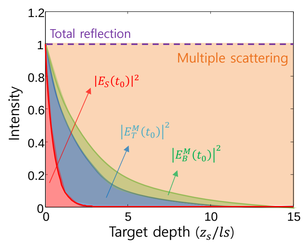
BS : Beam splitter
OL : Objective lens
DG : Diffraction grating
SM : Scanning mirror
SLM : Spatial light modulator
Ti:S : $\lambda_0 = 780\,nm$, $\Delta\lambda = 30\,nm$

- ✓ Time-gated detection using low coherence light source.
- ✓ Wide-field detection by off-axis interferometry.
- ✓ Wavefront shaping to control the incident angle.
- ✓ Red curve indicates phase modulated wave from randomly chosen SLM pixels, and blue curve indicates unmodulated one.

Principles

Time-gated measurement





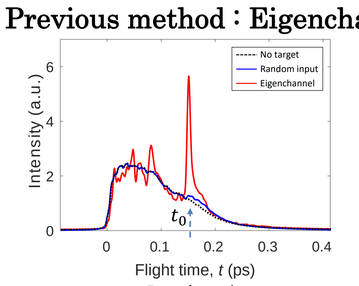
$E_R(t_0) = E^S(t_0) + E_T^M(t_0) + E_B^M(t_0)$

E^S: single-scattered waves from target
E_T^M: multiple-scattered waves from target
E_B^M: multiple-scattered waves from media

$I_S(z_s) = I_0 \exp(-2z_s/l_s)$

- ✓ 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

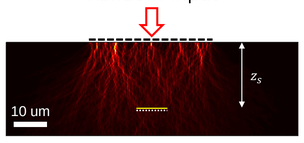


$E_j^{(out)} = \sum_i t_{ji} E_i^{(out)} \quad t = U\,\tau\,V^\dagger$

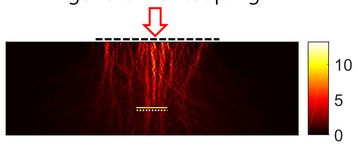
$\vec{E}^{(out)} = t\,\vec{E}^{(in)} \qquad \vec{E}^{(out)} = U\,\tau\,V^\dagger \vec{E}^{(in)}$

t : Matrix input-output relation information of sample
U : Output eigenchannel
V : Input eigenchannel
τ : Diagonal matrix with eigenvalue (Amplitude of eigenchannel)

Random input

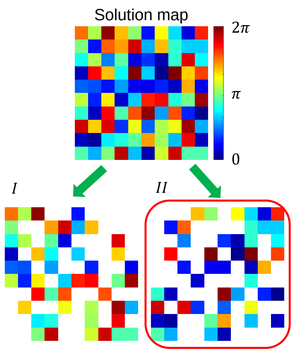


Eigenchannel coupling



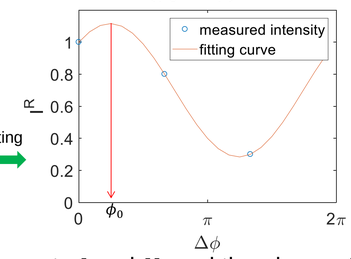
- ✓ Theoretically, eigenchannel can transmit light perfectly through the scattering medium by wavefront control.
- ✓ Light energy delivered to target is enhanced with time-gated reflection eigenchannel.
- ✓ This method should measure the matrix that characterizes the objects, which needs stable condition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

Iterative phase modulation of time-gated reflection wave



$\boldsymbol{E}^R(t, \Delta\phi) = \sum_{i=1}^N \left[c_i^I \sigma_i \boldsymbol{u}_i + c_i^{II} \sigma_i \boldsymbol{u}_i e^{i\Delta\phi}\right]$

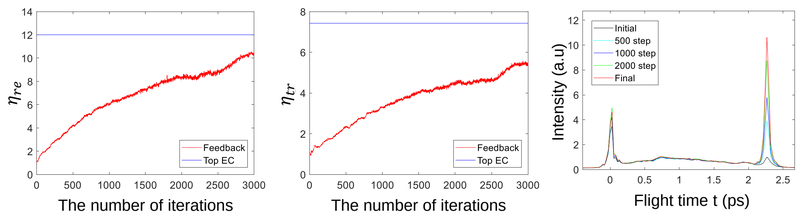
$I^R(t, \Delta\phi) = |\boldsymbol{E}^R(t, \Delta\phi)|^2 = \sum_{i=1}^N \tau_i \left|c_i^I + c_i^{II} e^{i\Delta\phi}\right|^2$
$= A + B\cos(\phi_0 + \Delta\phi)$



- ✓ 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.

Experimental results

Reflection & transmission enhancement

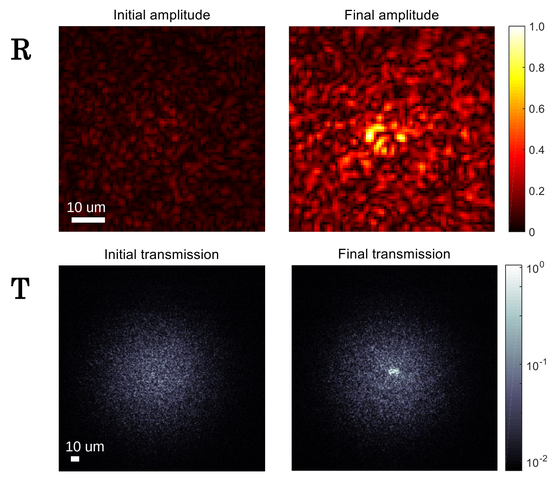


η_{re} : Reflection enhancement of target area for a specific time
η_{tr} : Transmission enhancement at the target area

- ✓ With increase of the number of iterations, both time-gated reflection and transmission intensities are simultaneously optimized.
- ✓ Enhancement of time-gated reflection feedback is nearly close to time-gated eigenchannels.
- ✓ We measured the reflection temporal response by controlling the length of reference arm.
- ✓ Feedback approach can affect the reflection of only specific time.

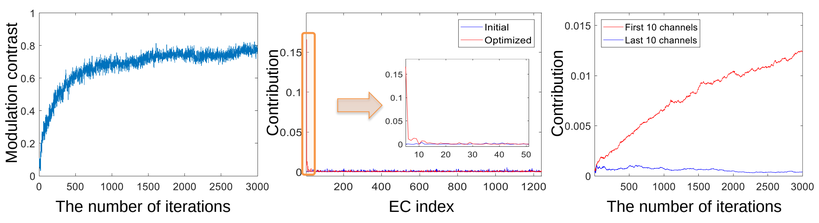
Experimental result

Reflection & transmission image of feedback solution



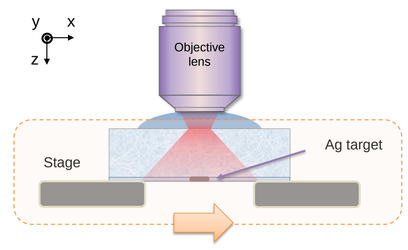
- ✓ Optimized solution enhances the intensity of only target area when time-gating was setting to flight time of target depth.

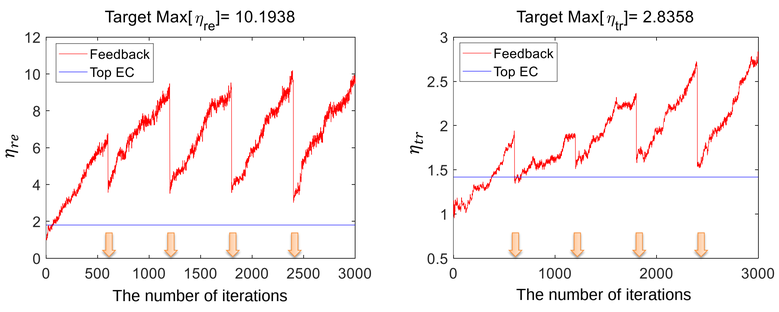
Convergence to eigenchannel with largest eigenvalue



- ✓ Maximization of modulation contrast means that the feedback input converges to the eigenchannel with the largest eigenvalue.
- ✓ Each eigenchannel has equally contributed to the initial feedback input, but the contribution of eigenchannel with the largest eigenvalue is extremely higher in optimized feedback solution.
- ✓ As the increase of the iteration number, the contribution of high-reflection eigenchannels become higher.

Overcoming the effect of sample drift





- ✓ External perturbation was given during the optimization.
  (Arrows : Sample stage was moved by 1 um along the x-axis)
- ✓ Enhancement was drastically dropped when the stage was shifted.
- ✓ Feedback method optimized the signal from the moved target, and the enhancement was quickly recovered.
- ✓ Matrix method was not effective when sample stage was moving.
  (blue line)

Summary

- ✓ By combining time-gated detection and iterative feedback algorithm for wavefront shaping, 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 of time-gated reflection feedback method.
- ✓ We validated that time-gated iterative feedback optimization resembles with the high-reflection time-gated eigenchannels.
- ✓ We confirmed that time-gated reflection feedback method is effective to the perturbed target, unlike the matrix measurement method.

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