Focusing of light energy inside scattering media by controlling the time-gated multiple light scattering

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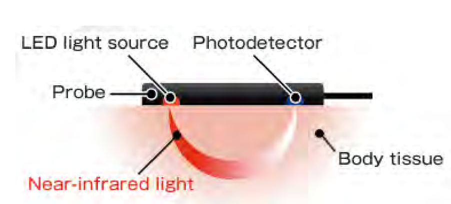
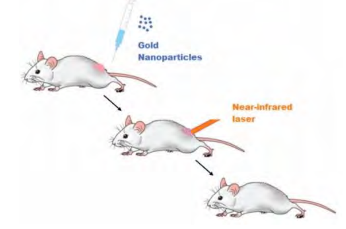
Motivation : Biomedical application of optical methods

- Optical microscopy
- Biosensing

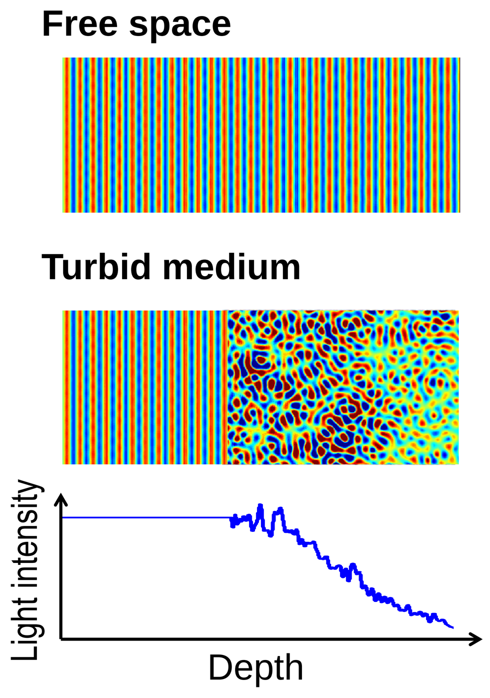



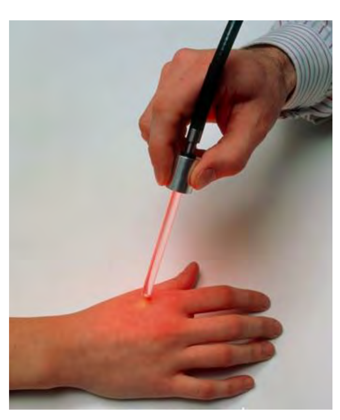
- Optogenetics
- Photothermal therapy

✓ If the light can be delivered deep under skin tissue, working depth of optical methodology can be enhanced.

Problem : Attenuation of light energy

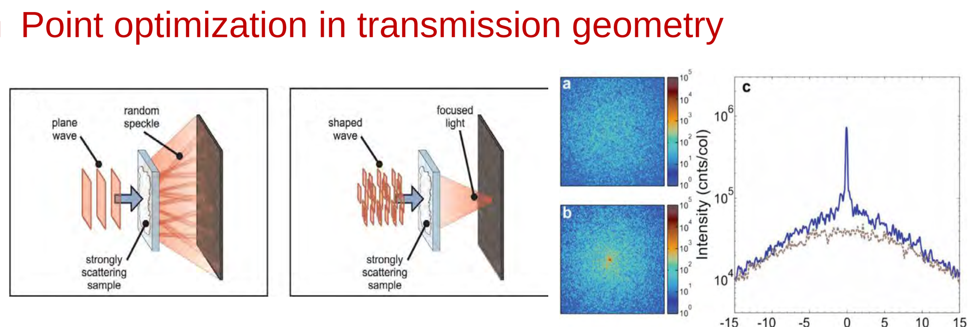




✓ **Fundamental limitation to *in vivo* sensing and control**

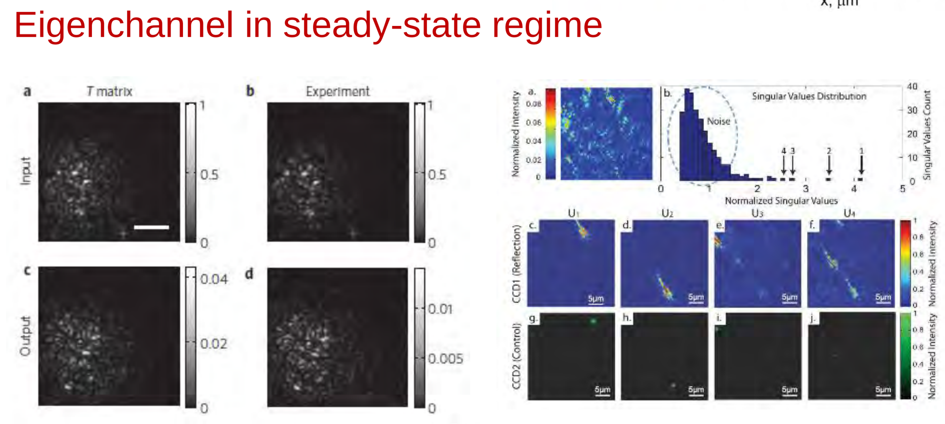
Previous study with wavefront shaping

- Point optimization in transmission geometry



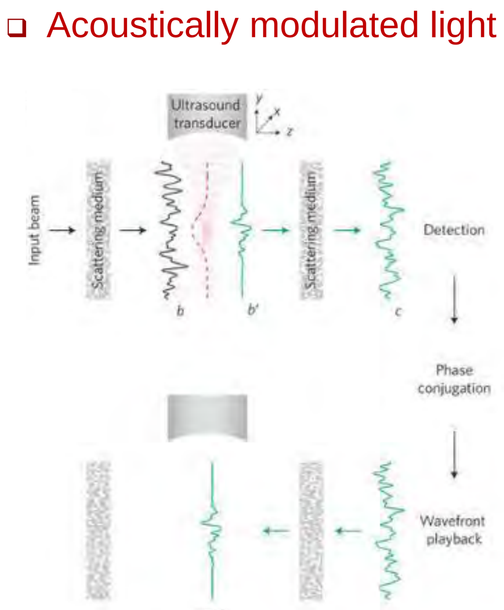
[1]

- Eigenchannel in steady-state regime



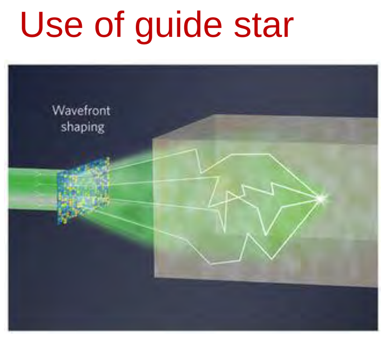
[2] [3]

- Acoustically modulated light



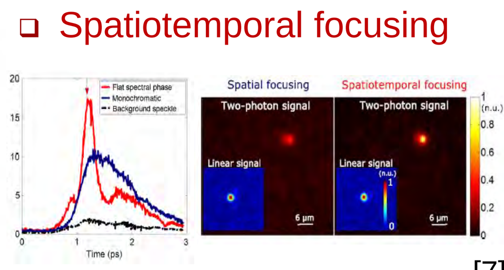
[4,5]

- Use of guide star



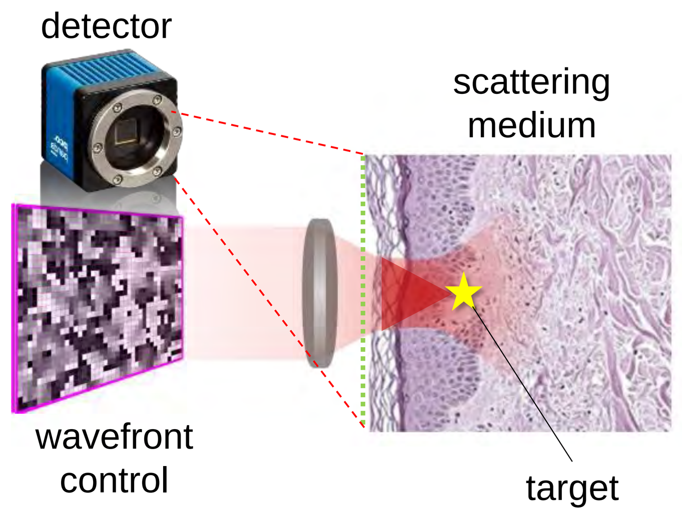
[6]

- Spatiotemporal focusing



[7]

Research goal : Time-gated reflection eigenchannel



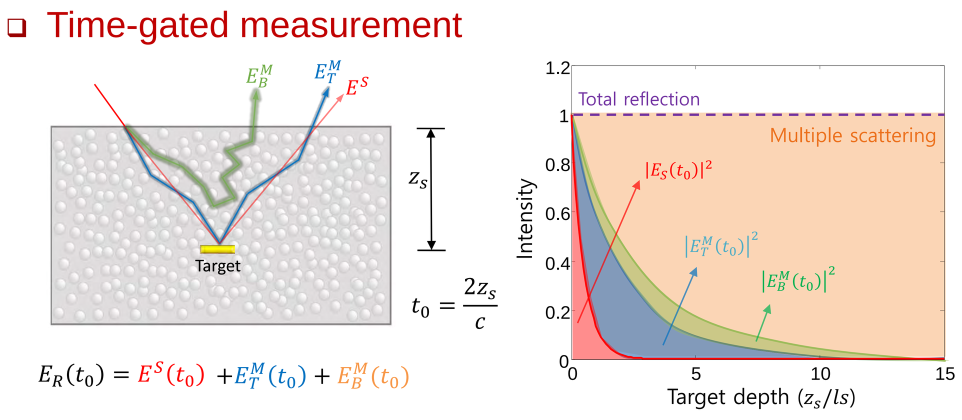
***In-vivo* compatible!**

- reflection geometry
- in scattering medium
- without labeling agent

✓ Our goal is to focus light energy into the target deep embedded in scattering media.

Principle : Time-gating + Eigenchannel

- Time-gated measurement



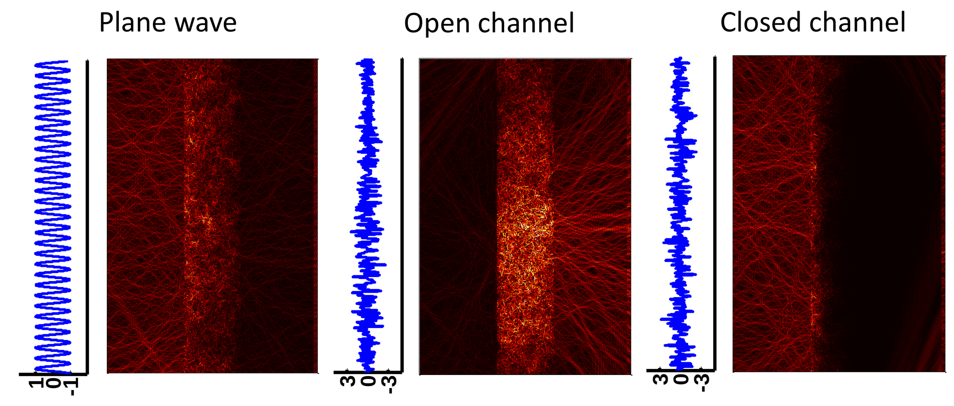
$E_R(t_0) = E^S(t_0) + E_T^M(t_0) + E_B^M(t_0)$

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 $E_R(t \neq t_0)$
✓ For the case of deeply embedded target, the most of time-gated signal is multiple-scattered waves from target.

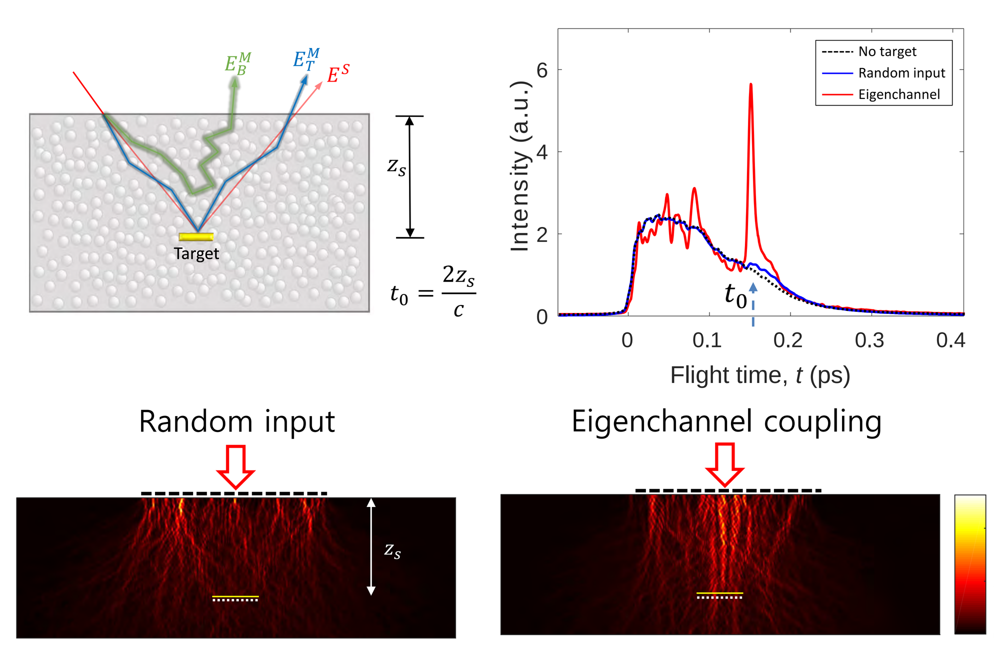
- Eigenchannel writing



[8,9]

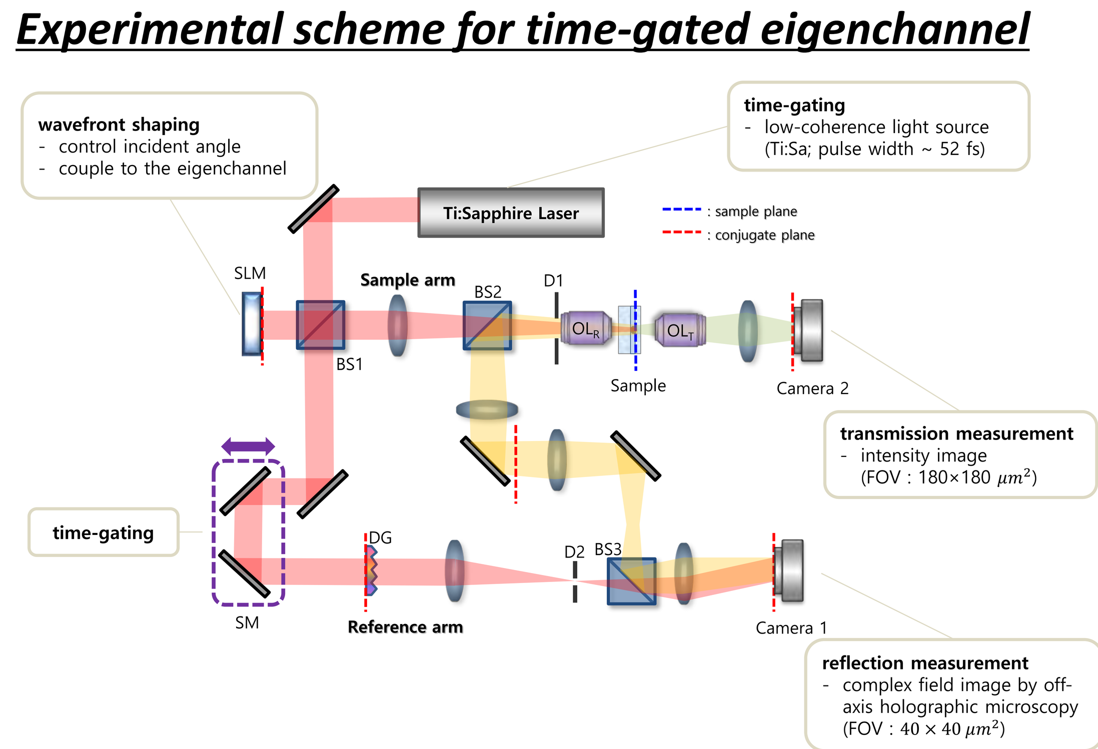
✓ Open channel means perfect transmission theoretically.
✓ Wave propagation is controlled by wavefront shaping.
✓ How about the top eigenchannel of time-gated reflection matrix?

FDTD simulation of time-gated reflection eigenchannel

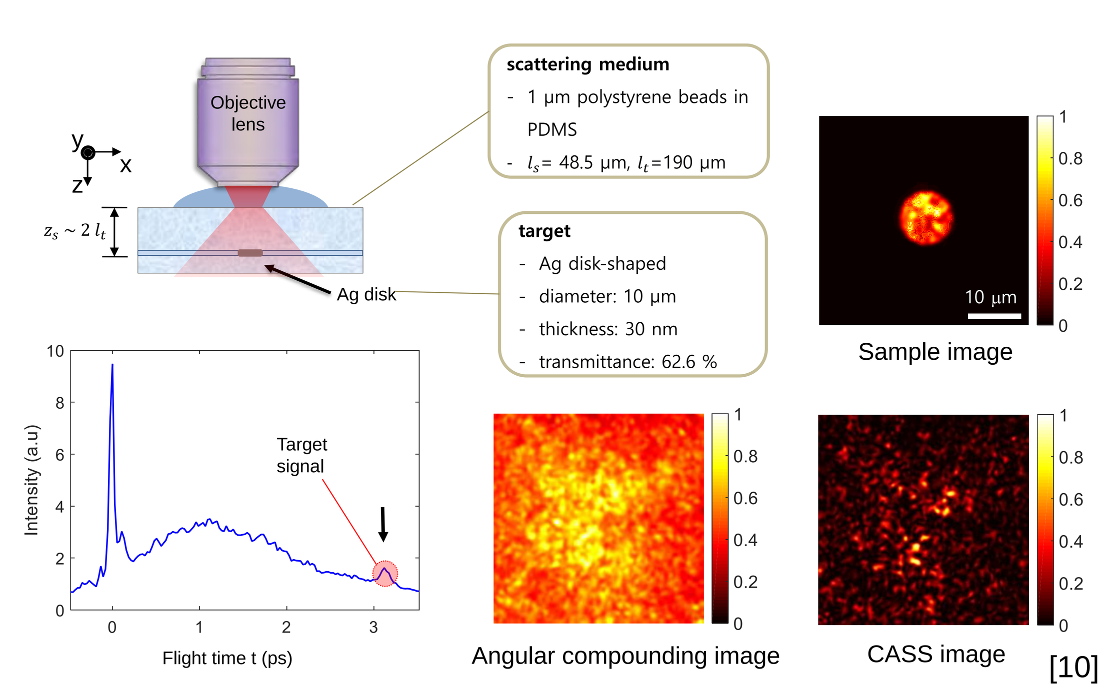


✓ Light energy delivery is enhanced with time-gated reflection eigenchannel

Experimental scheme for time-gated eigenchannel

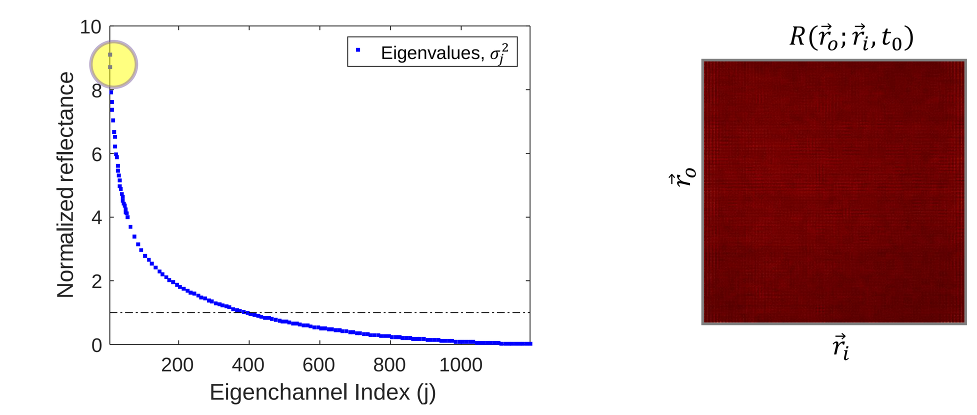


Sample preparation: The embedded target



[10]

Eigenchannel of time-gated reflection matrix

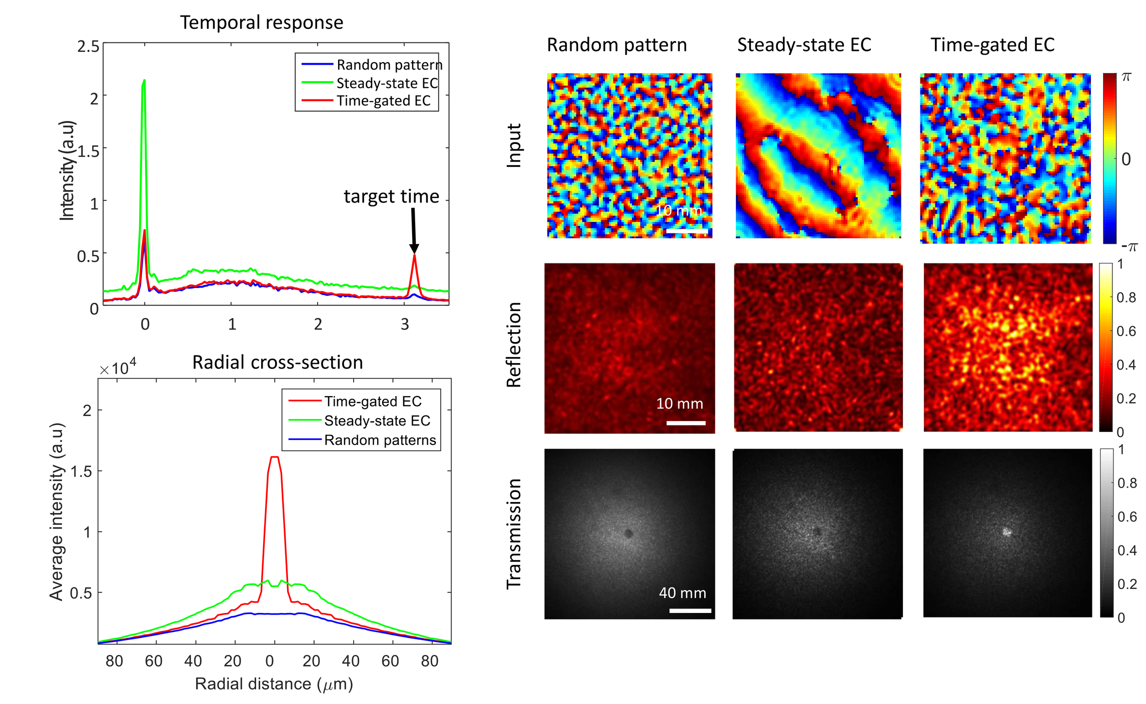


Matrix measurement
$\vec{E}_R(t_0) = R(t_0)\vec{E}_{(in)}$
1600 angle within 0.4 NA
FOV (Field of view): $40 \times 40\ \mu m^2$

⇨ **Singular value decomposition (SVD) :** $R = U\Sigma V^\dagger$
U : Output eigenchannel
V : Input eigenchannel
Σ : Diagonal matrix with eigenvalue

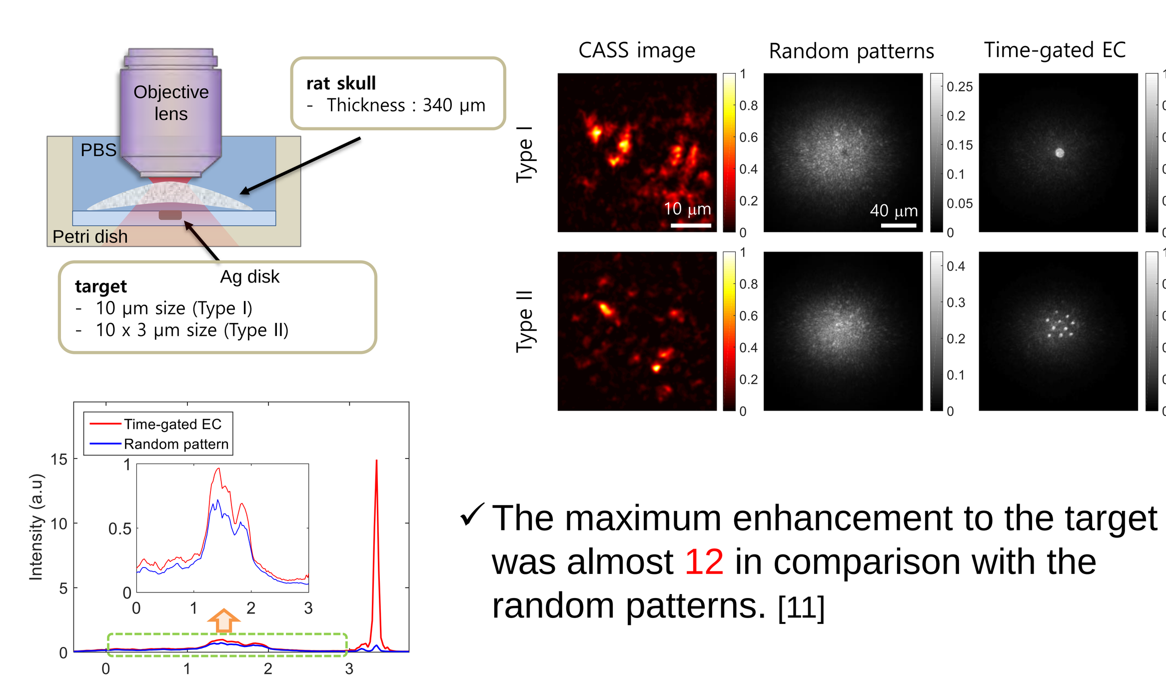
⇨ **Wavefront shaping with SLM**
$\vec{E}_R(t_0) = U\Sigma V^\dagger \vec{E}_{(in)}$
$\vec{E}_{(in)} = \vec{v}_j$
$\vec{E}_R(t_0) = \sigma_j \vec{u}_j$

Focusing of light energy into the embedded target



✓ *4 times enhancement* of reflection and transmission for the target at 1.7 l_t in comparison with the random patterns.

Light energy delivery through rat skull



✓ The maximum enhancement to the target was almost 12 in comparison with the random patterns. [11]

Conclusion

✓ We demonstrate the experimental injection of time-gated reflection eigenchannels at first.

✓ We could focus light energy into the target object embedded deep inside scattering media with the time-gated reflection eigenchannel.

✓ Time-gated reflection eigenchannel can focus light energy into the target to control multiple scattered waves from the target.

✓ Time-gated reflection eigenchannel can deliver light energy into the target through biological structure such as rat skull.

Reference

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