Focusing of light energy inside a scattering medium using time-gated reflection eigenchannel

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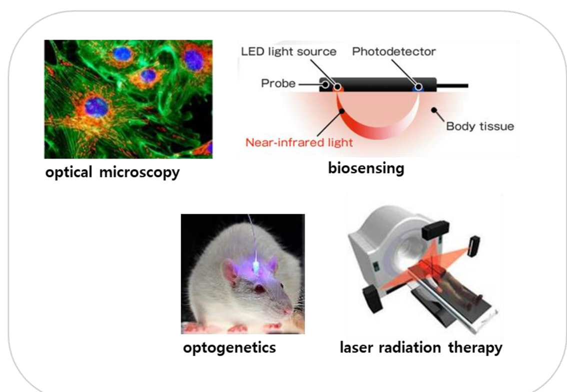
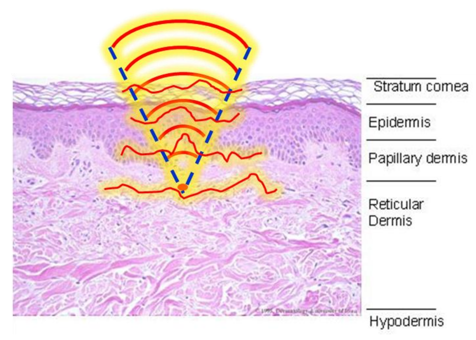
Motivation

- Optical imaging/sensing/stimulation require ***efficient light energy delivery*** to objects of interest embedded within scattering medium.

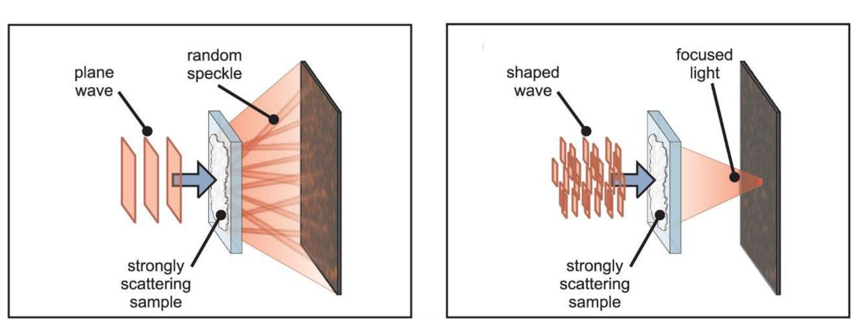




Limitation from random diffusion

Previous Work

Wavefront shaping

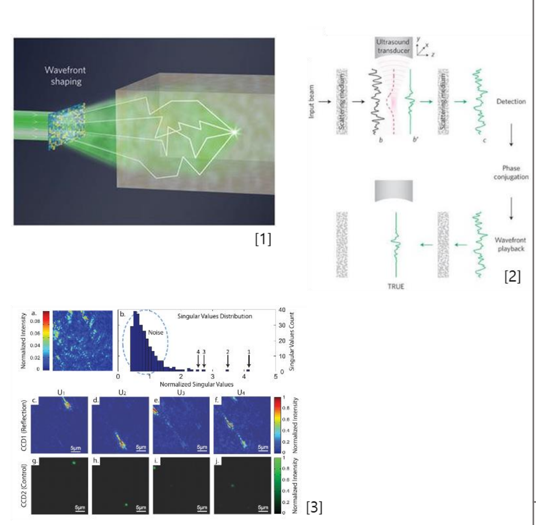


transmission geometry

I. M. Vellekoop and A. P. Mosk, Opt Lett 32, 2309 (2007)
O. Katz et al., Nat Photonics 5, 372 (2011)
J. Aulbach et al., Opt Express 20, 29237 (2012)
M. Mounaix et al., Phys Rev Lett 116, 253901 (2016)
M. Kim et al., Nature Photonics 6, 583 (2012)

Embedded target

- Time-reversal of the acoustically modulated optical wave
  X. Xu et al., Nat Photonics 5, 154 (2011)
  B. Judkewitz et al., Nat Photonics 7, 300 (2013) [2]
- Guide star method
  P. N. Marsh et al., Opt Express 11, 1123 (2003)
  I. M. Vellekoop et al.,Opt Express 16, 67 (2008)
  N. Ji et al., Nat Methods 7, 141 (2010)
  R. Fiolka et al., Opt Express 20, 16532 (2012)
  C. Wang et al., Nat Methods 11, 1037 (2014)
- Steady-state reflection eigenchannel
  S. M. Popoff et al., Phys Rev Lett 107 (2011) [3]
  C. Prada et al., J Acoust Soc Am 90, 1119 (1991)

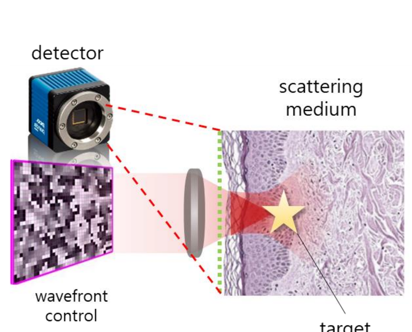


[1] R. Horstmeyer et al., Nature Photonics 9, 563–571 (2015)

Our Approach

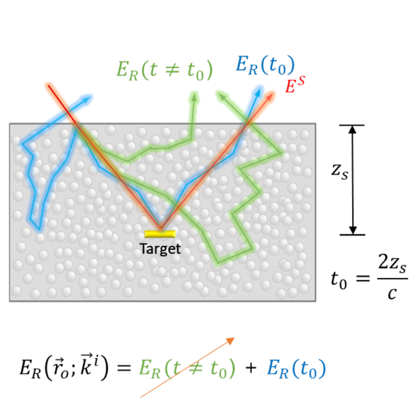
- **Time-gated reflection eigenchannel**
  - Reflection geometry
  - in scattering medium
  - w/o labeling agent

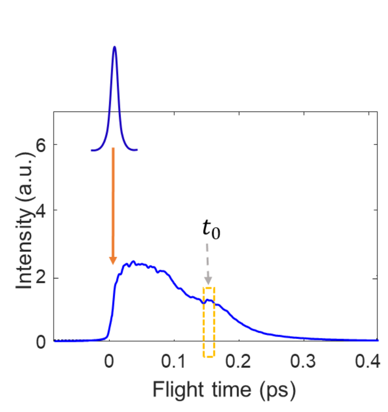
***in vivo* compatible!**



reflection geometry

First step: Time gating

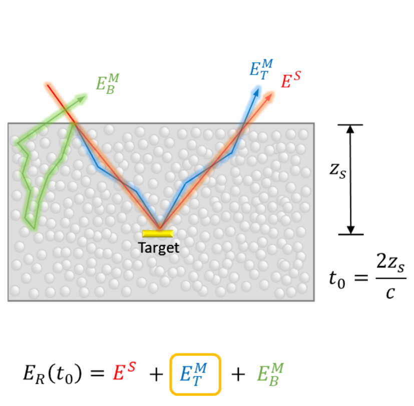


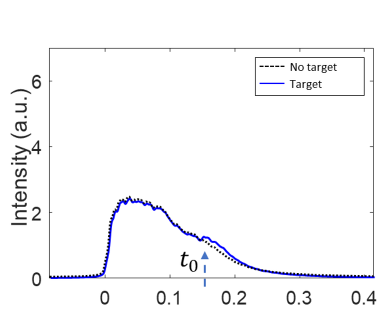


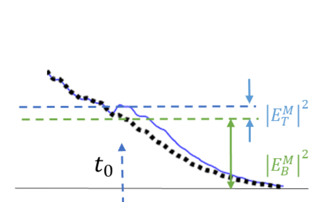
- This removes the multiple-scattered waves $E_R(t\neq t_0)$,
  : a few orders of magnitude stronger than $E_R(t_0)$ for a deeply embedded target.

Second step: Eigenchannel coupling

- find eigenchannels of R in order to maximize the total backscattering intensity set by R
- maximizing the total intensity → enhancing target energy delivery?
  even when $|E_T^M|^2 < |E_B^M|^2$







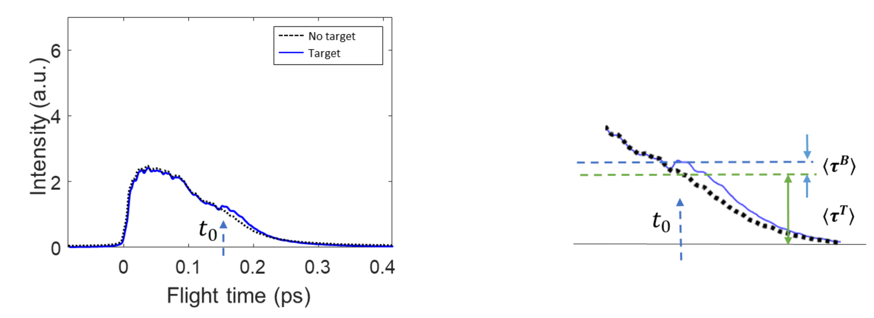
Principle – two important parameters

$R \approx M_T + M_B$,

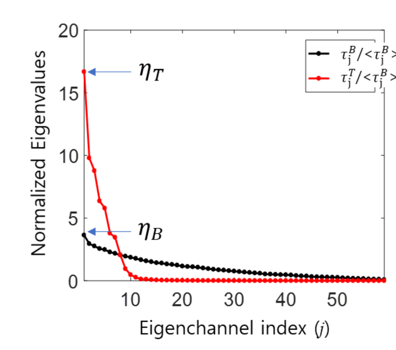
where M_T and M_B are constructed from E_T^M and E_B^M.

→ interplay between M_T and M_B in determining v_1^R.

1. average eigenvalue, $\langle\tau^T\rangle$ and $\langle\tau^B\rangle$
   - the **average intensities** of the target and background multiple-scattered waves.



2. enhancement factors, η_T and η_B
   - $\eta_T = \tau_1^T/\langle\tau^T\rangle$, $\eta_B = \tau_1^B/\langle\tau^B\rangle$
   - the **effectiveness** of the wavefront control
   - $\eta_T > \eta_B$ for targets smaller than the field of view: reduced number of effective channels → increased correlation among channels. [1]



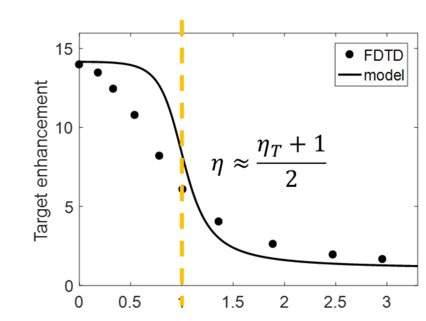
[1] C. W. Hsu et al., Nat. Phys. 13, 497 (2017)

If $\eta_T > \eta_B$ and $\langle\tau^T\rangle = \langle\tau^B\rangle$,

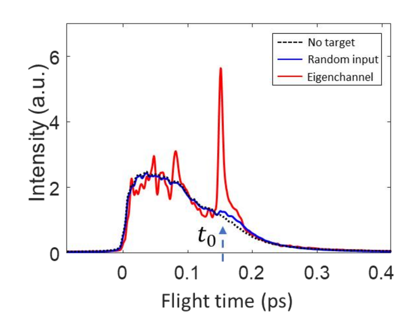
light wave **injected to v_1^R** will preferably couple its energy to M_T rather than M_B because $\eta_T > \eta_B$.

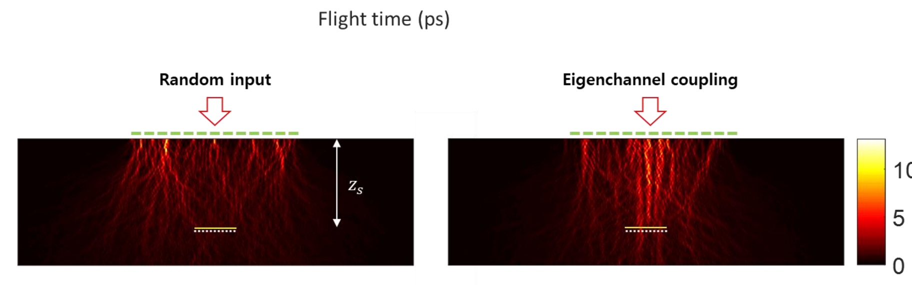
***preferable* enhancement of light energy delivered to the target object.**

$$\chi \equiv \frac{\eta_B - 1\langle\tau_B\rangle}{\eta_A - 1\langle\tau_A\rangle}$$



FDTD simulation

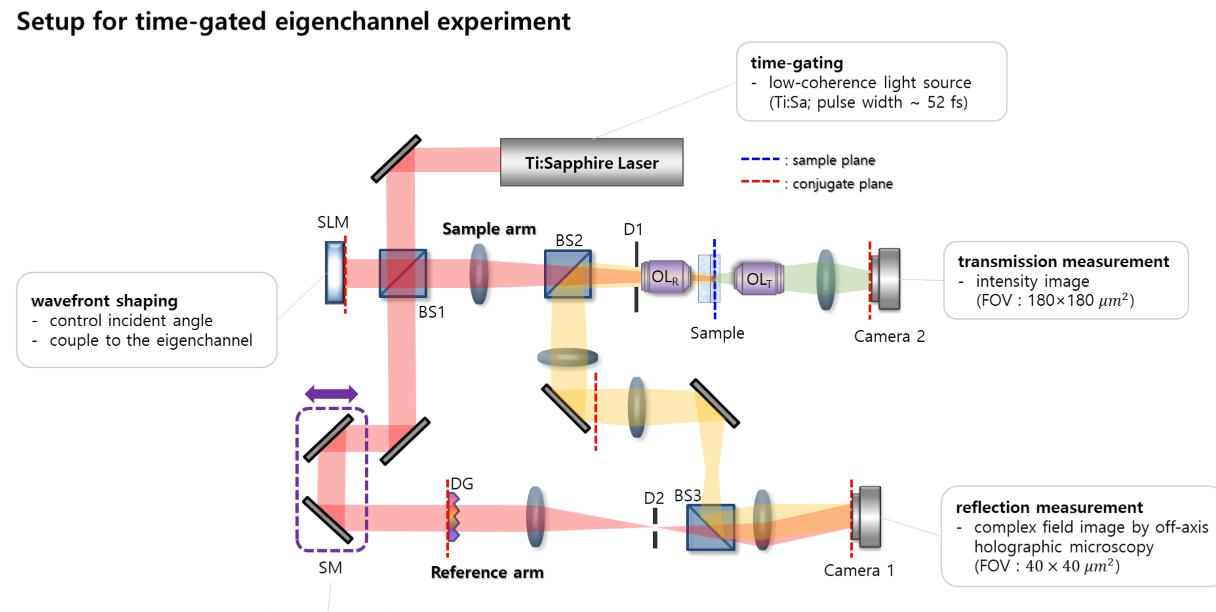




~ **x8** enhanced energy delivery to the target!

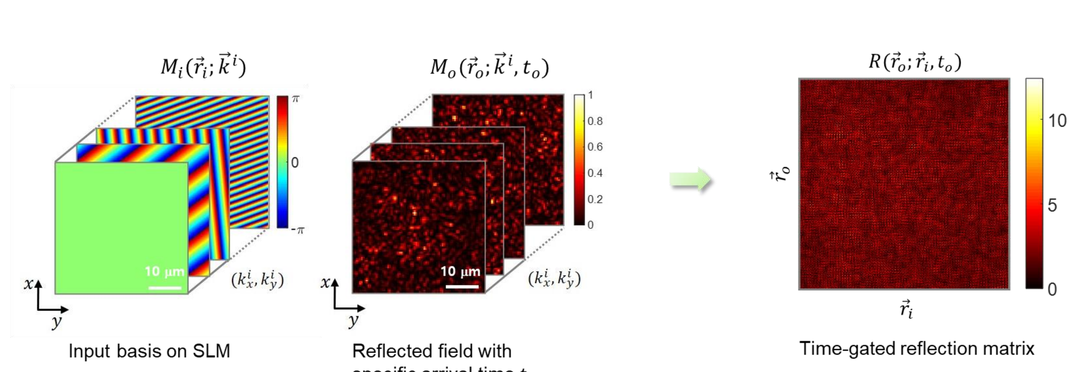
Experimental Results

Setup for time-gated eigenchannel experiment



Sungsam Kang, Seungwon Jeong et al., *Nature Photonics* **9**, 253 (2015)

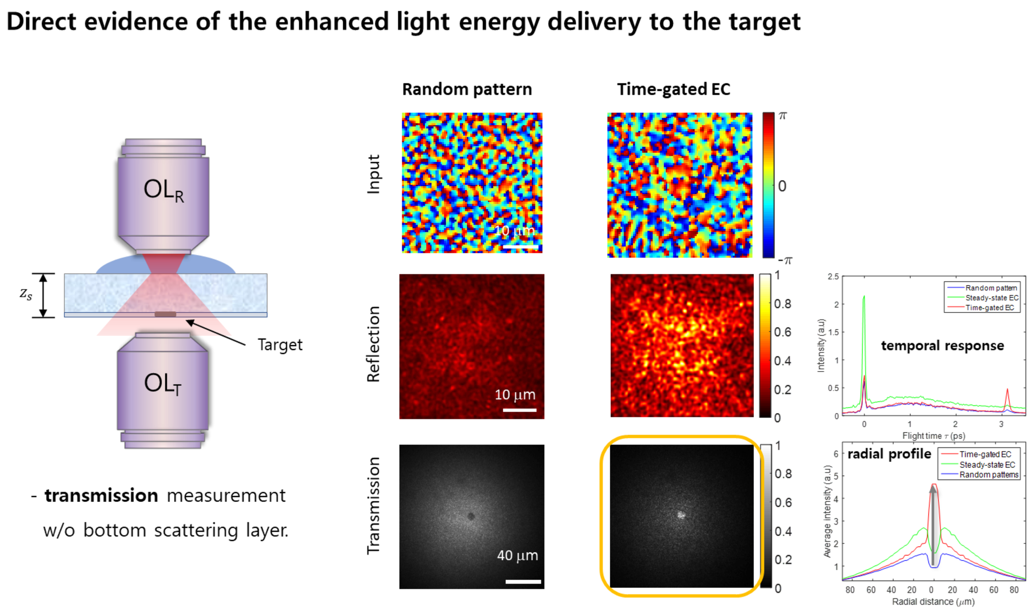
Construction of time-gated reflection matrix



$$R(\vec r_o;\vec r_i,t_o) = M_o(\vec r_o;\vec k^i,t_o)\ M_i(\vec r_i;\vec k^i)^{-1}$$

Singular value decomposition(SVD) of $R(\vec r_o;\vec r_i,t_o)$ → eigenchannels v_j^R → wavefront shaping with SLM

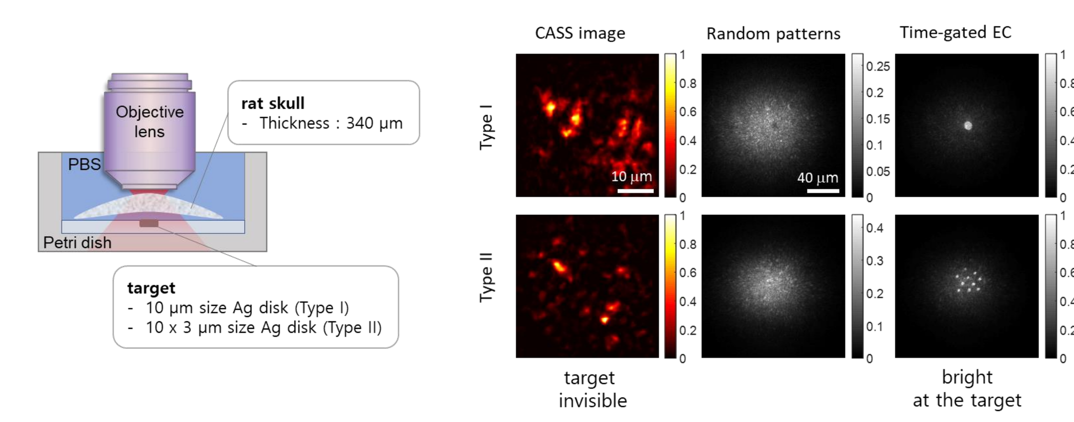
Direct evidence of the enhanced light energy delivery to the target



- **transmission** measurement w/o bottom scattering layer.

bright at the target

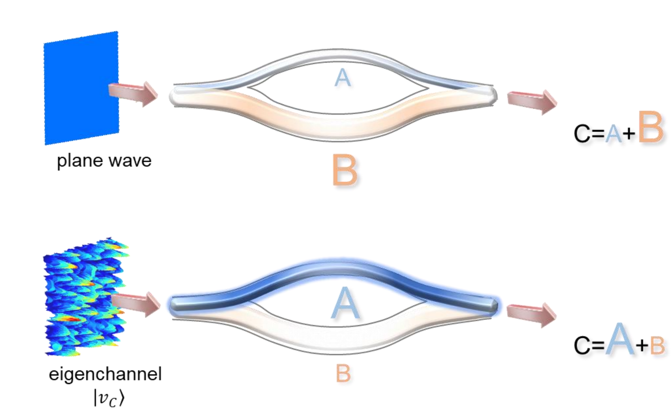
Demonstration of enhanced light energy delivery through a rat skull



~ **x12** target energy delivery enhancement

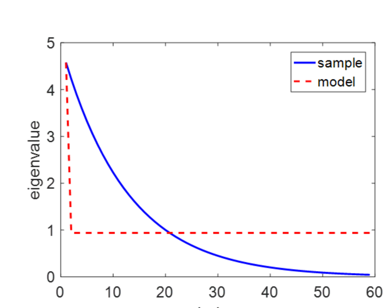
Nature Photonics 12, 277–283 (2018)

Analytic Framework for Understanding the Competing Processes



Find $|v_C\rangle$ maximizing total output energy (E_C) given $\langle\tau^A\rangle$, $\langle\tau^B\rangle$, η_A and η_B.

Assumption



$$|v_C\rangle = \sqrt{\alpha_A}e^{i\phi_{A,1}}|v_{A,1}\rangle + \sum_{i=2}^{N}\sqrt{\frac{1-\alpha_A}{N-1}}e^{i\phi_{A,i}}|v_{A,i}\rangle$$

$$|v_C\rangle = \sqrt{\alpha_B}e^{i\phi_{B,1}}|v_{B,1}\rangle + \sum_{i=2}^{N}\sqrt{\frac{1-\alpha_B}{N-1}}e^{i\phi_{B,i}}|v_{B,i}\rangle$$

Find α_A, $\phi_{A,i}$, α_B, and $\phi_{B,i}$ that maximize E_C.

Constraint

$$E_C = \langle v_C|C^*C|v_C\rangle \cong \langle v_C|A^*A|v_C\rangle + \langle v_C|B^*B|v_C\rangle$$

$$E_C = \frac{N}{N-1}\langle\tau_A\rangle[(\eta_A-1)\boldsymbol{\alpha_A} - \eta_A/N + 1] + \frac{N}{N-1}\langle\tau_B\rangle[(\eta_B-1)\boldsymbol{\alpha_B} - \eta_B/N + 1]$$

$$\boxed{|v_C\rangle\langle|v_A\rangle\rangle = |v_C\rangle\langle|v_B\rangle\rangle}$$

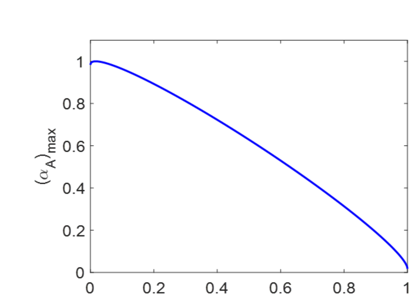
if A and B are independent

$$|v_{B,j}\rangle = \frac{1}{\sqrt N}\sum_{i=1}^{N}e^{i\theta_{ji}}|v_{A,i}\rangle$$

$$\alpha_A = \frac{1}{N}\left|\sqrt{\alpha_B}e^{i\phi_{B,1}}e^{i\theta_{11}} + \frac{\sqrt{1-\alpha_B}}{\sqrt{N-1}}\left(\sum_{i=2}^{N}e^{i\phi_{B,i}}e^{i\theta_{i1}}\right)\right|^2$$

find $e^{i\phi_{B,i}}$ maximizing α_A

$$(\alpha_A)_{\max} = \frac{1}{N}\left(\sqrt{\alpha_B}+\sqrt{N-1}\sqrt{1-\alpha_B}\right)^2$$



find α_B maximizing E_C

$$E_C = \frac{N}{N-1}\langle\tau_A\rangle[(\eta_A-1)\boldsymbol{\alpha_A} - \eta_A/N + 1] + \frac{N}{N-1}\langle\tau_B\rangle[(\eta_B-1)\boldsymbol{\alpha_B} - \eta_B/N + 1]$$

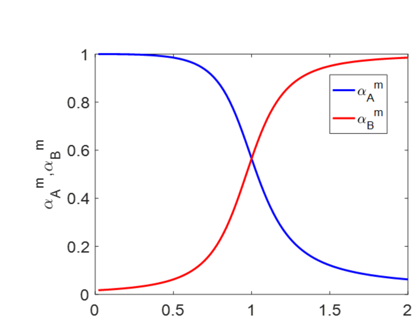
$$(\alpha_A)_{\max} = \frac{1}{N}\left(\sqrt{\alpha_B}+\sqrt{N-1}\sqrt{1-\alpha_B}\right)^2 \Rightarrow E_C(\alpha_B)$$

$$\boxed{\frac{dE_C(\alpha_B)}{d\alpha_B} = 0}$$

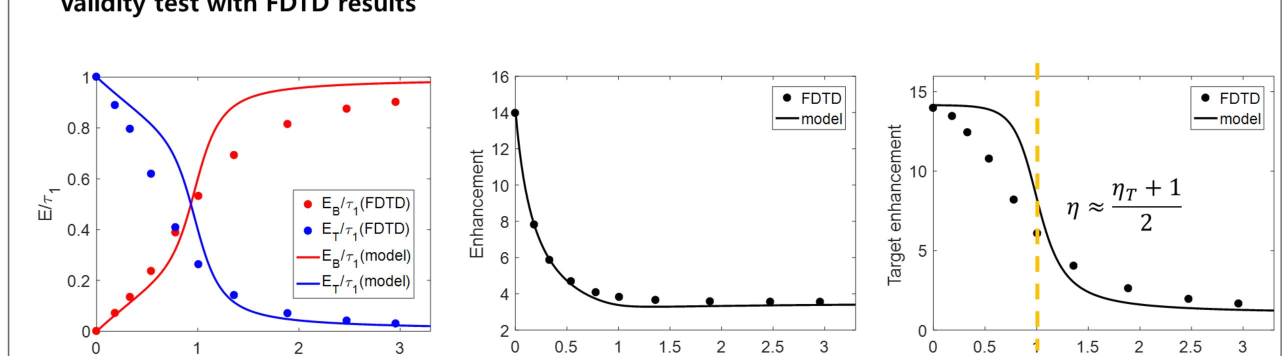
$$\alpha_B^m \approx \frac{1}{2} + \frac{1}{2}\frac{\chi-1}{\sqrt{\frac{4}{N}+(\chi-1)^2}}$$

$$\alpha_A^m \approx \frac{1}{2} + \frac{1}{2}\frac{\frac{1}{\chi}-1}{\sqrt{\frac{4}{N}+\left(\frac{1}{\chi}-1\right)^2}}$$

$$\left(\chi \equiv \frac{\eta_B - 1\langle\tau_B\rangle}{\eta_A - 1\langle\tau_A\rangle}\right)$$



Validity test with FDTD results



Scientific Reports 9, 2785 (2019)

Summary

- presented the *first* experimental coupling of light to the time-gated reflection eigenchannels
- demonstrated both theoretically and experimentally that this eigenchannel coupling preferably enhances those multiple-scattered waves interacted with a target
- enhanced light energy delivery to a target deeply embedded in scattering medium (more than x10)
- Developed analytic framework for understanding the preferable coupling
- non-invasive method: particularly important for *in vivo* and *in situ* applications