Dynamics of the time-gated reflection eigenchannel in homogeneous scattering medium

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Analytic Framework for Understanding the Competing Processes

Motivation

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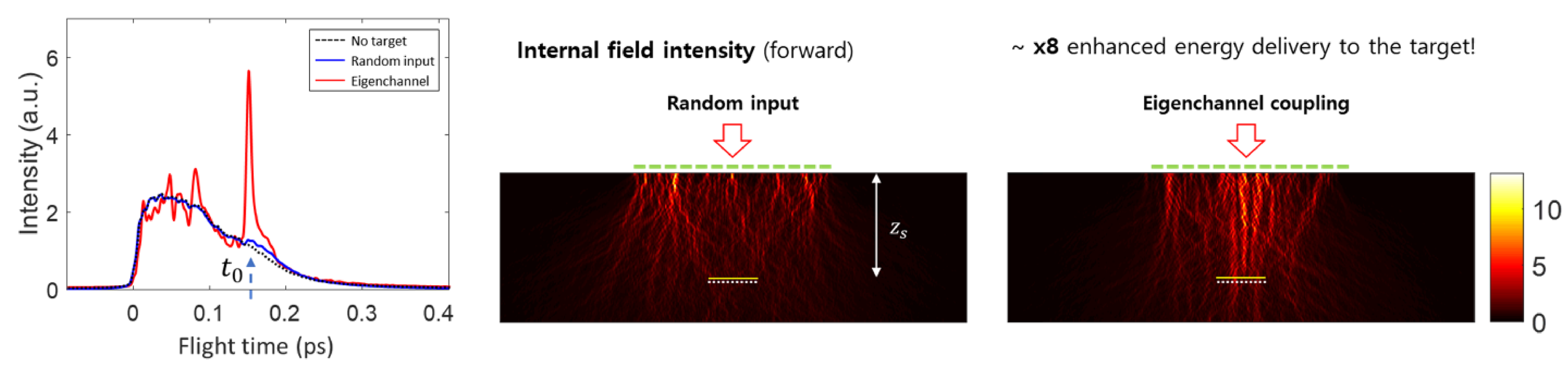
Focusing of light energy inside a scattering medium using time-gated reflection eigenchannel

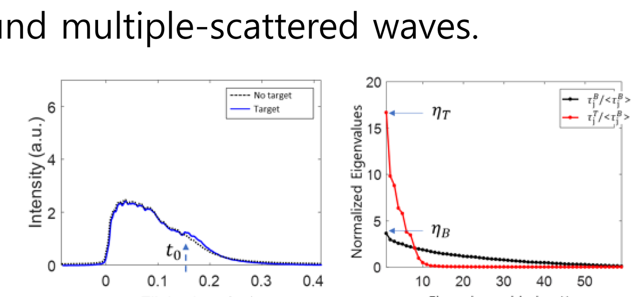


$$R \approx M_T + M_B$$

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

Two governing parameters

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



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.**

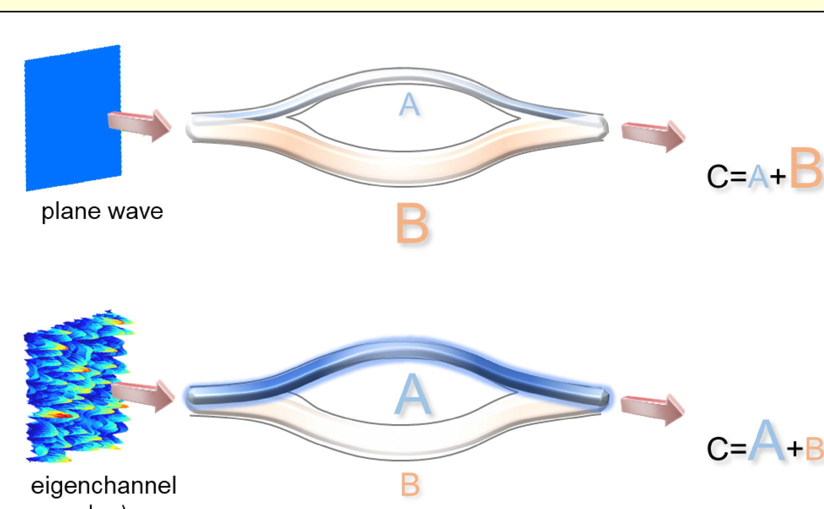
How can we analytically predict the working condition of this method using the two parameters?

Results

Scientific Reports 9, 2785 (2019)

Generalization

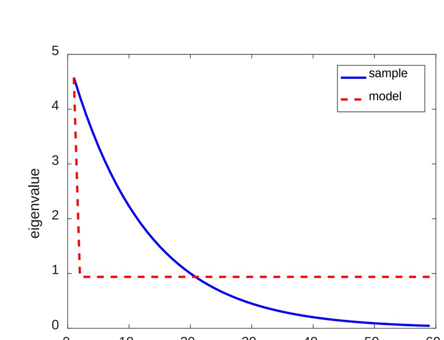
- **Find $|v_C\rangle$ maximizing total output energy (E_C) given $\langle\tau^A\rangle$, $\langle\tau^B\rangle$, η_A and η_B.**



Assumption

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

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



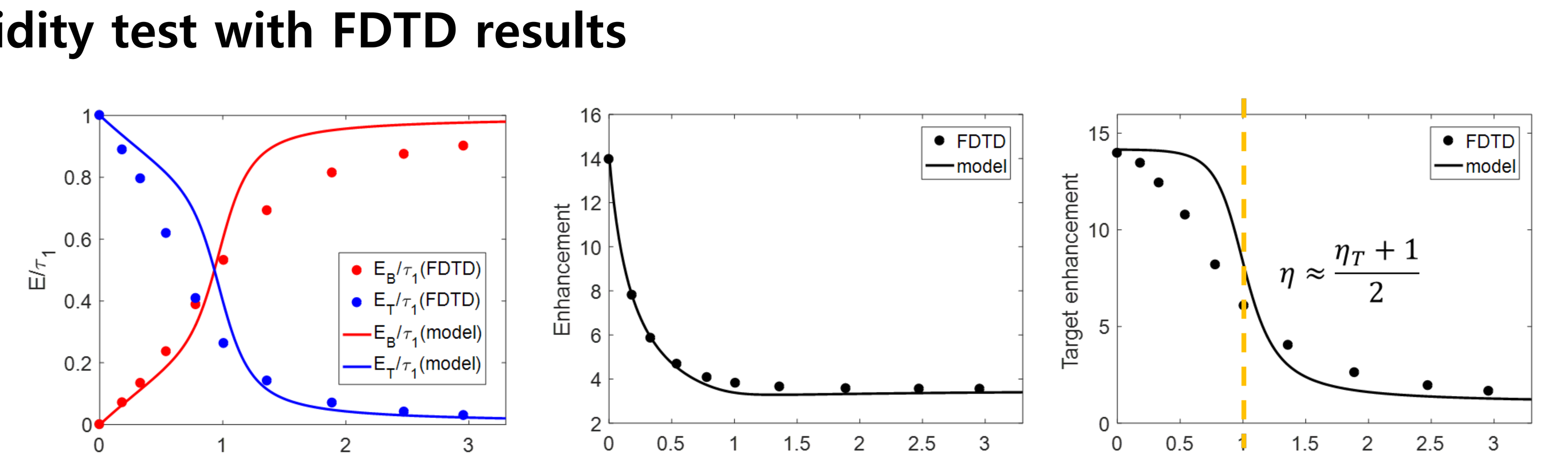
Find α_A and α_B that maximize E_C

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

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

$$\alpha_A^m \approx \frac{1}{2} + \frac{1}{2}\frac{\frac{1}{\chi}-1}{\sqrt{\frac{4}{N}+\left(\frac{1}{\chi}-1\right)^2}} \qquad \alpha_B^m \approx \frac{1}{2} + \frac{1}{2}\frac{\chi-1}{\sqrt{\frac{4}{N}+(\chi-1)^2}} \qquad \left(\chi \equiv \frac{\eta_B-1}{\eta_A-1}\frac{\langle\tau_B\rangle}{\langle\tau_A\rangle}\right)$$

Validity test with FDTD results



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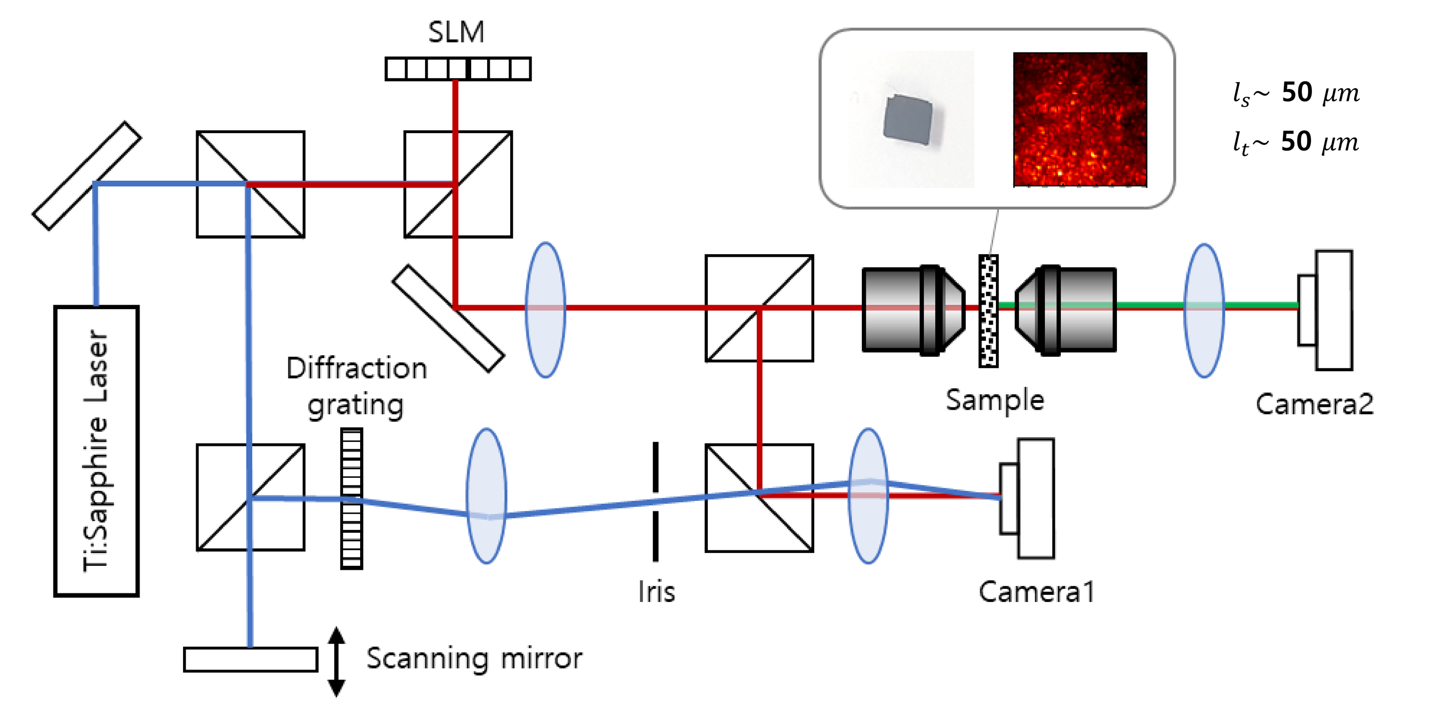
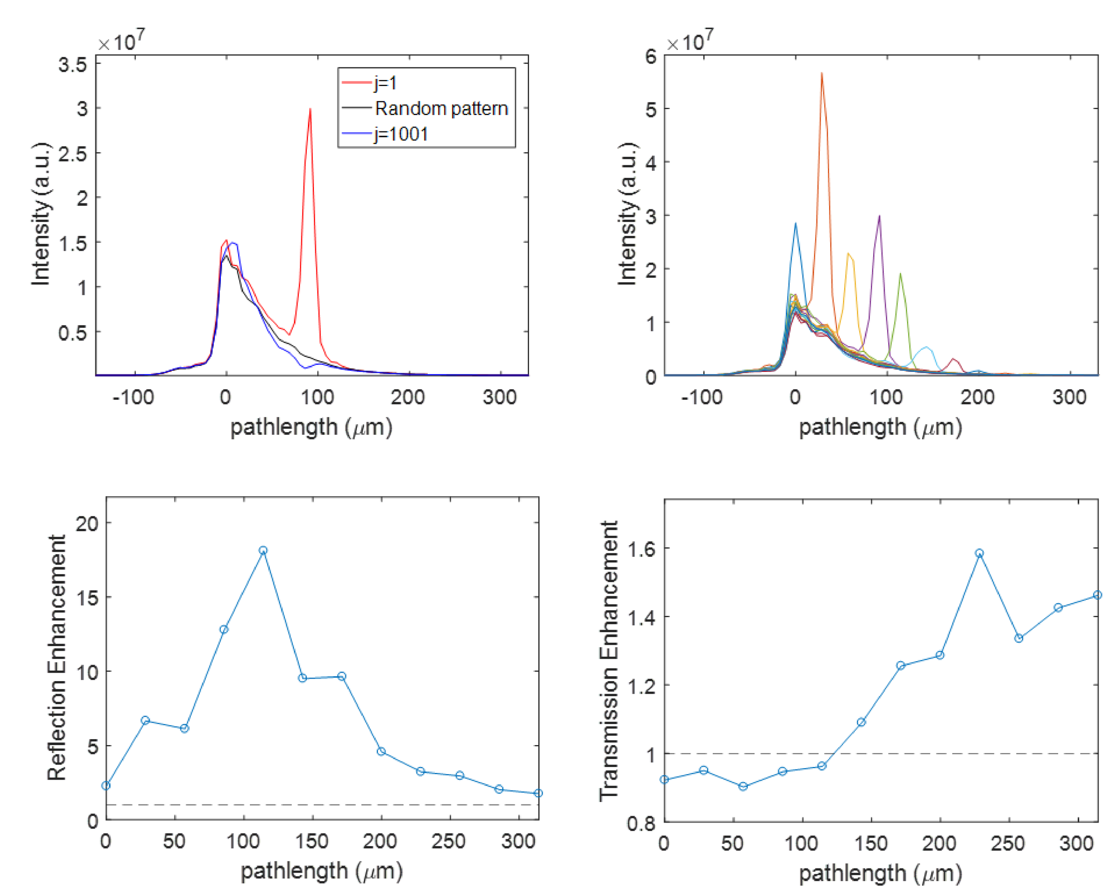
Experimental Results

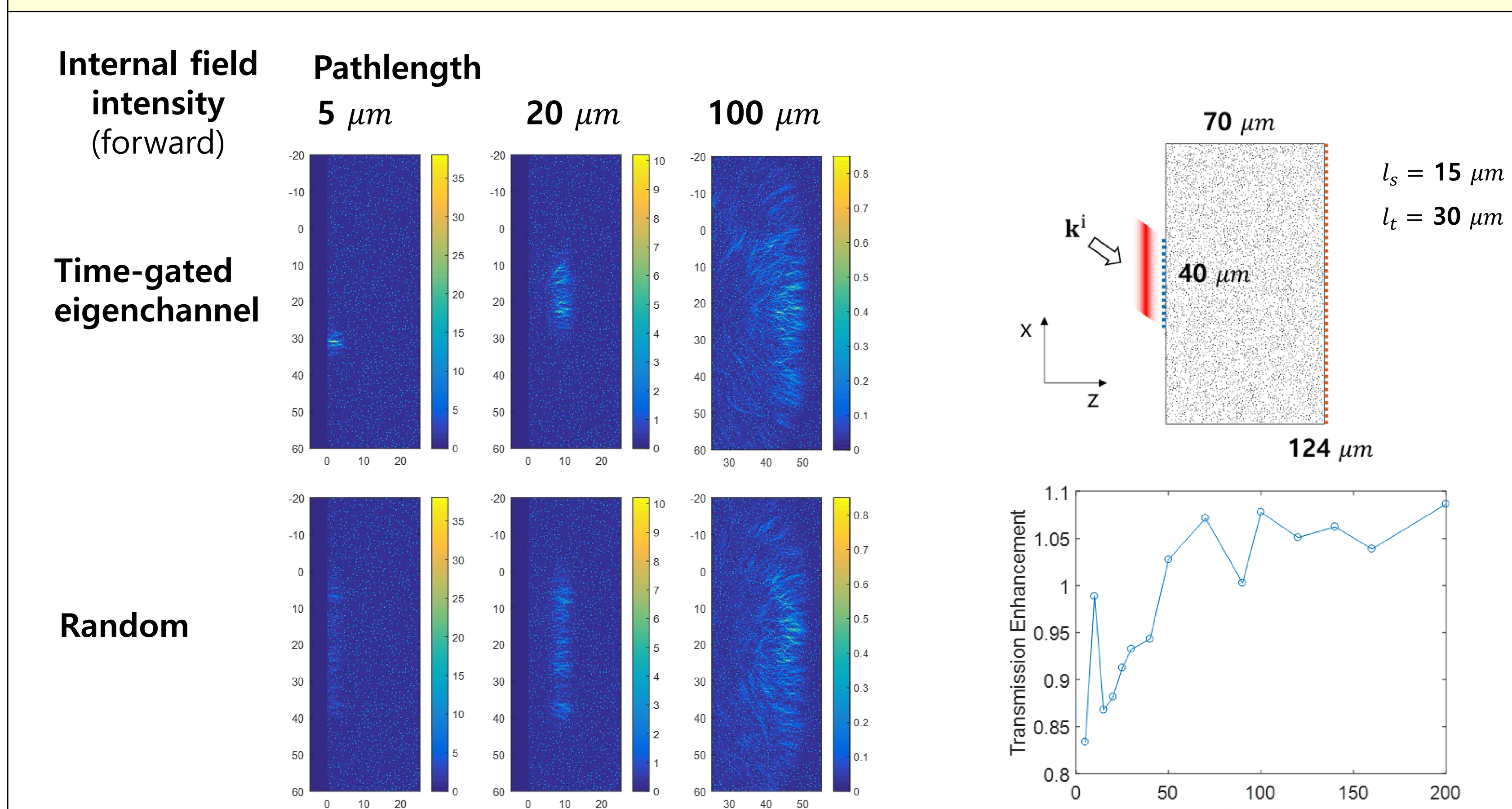




Transition behavior

- **Suppression to enhancement**

Simulation Results



Transition behavior in wave propagation

- **Focusing to diffusion**

Summary

- Derived an analytic expression describing the way the eigenchannel coupling of the total process distributes its energy to the individual subprocesses, with only partial information on each subprocess such as the average eigenvalue $\langle\tau\rangle$ and enhancement factor η.
- Found that the ratio of $(\eta-1)\langle\tau\rangle$ between two subprocesses is a critical parameter determining the preferable subprocess in the energy coupling.
- Experimentally observed transition behavior in transmission while tuning the target pathlength of the time-gated reflection eigenchannels.
- The internal field distribution from FDTD simulations showed transition behavior in wave propagation.