Optimal Wave Fields for Micro-Manipulation in Complex Scattering Environments

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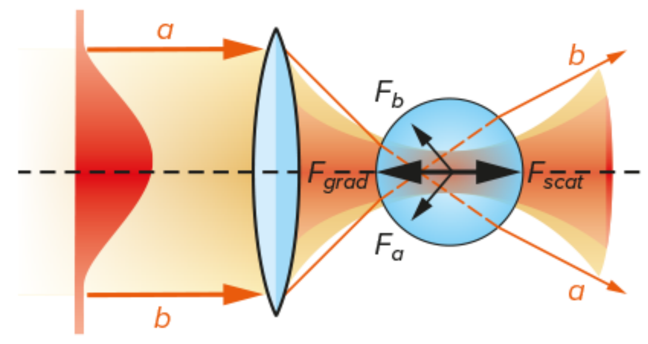
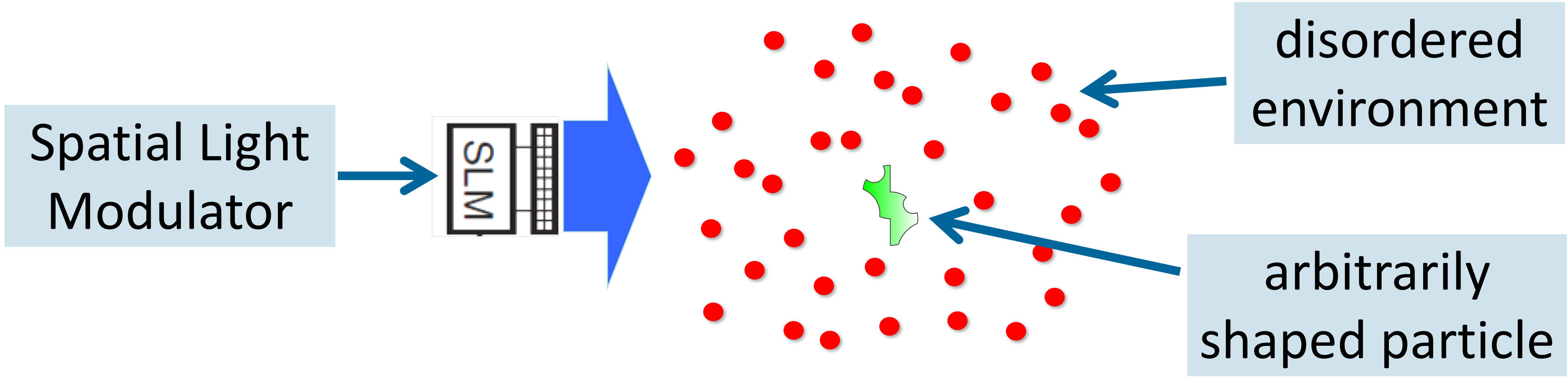
Motivation & Scope

- micro-manipulation: **move**, **hold**, **rotate** small **particles** by exertion of controllable **forces**
- seminal work[1]: **trap** particles using **optical beams**



- challenges: **non-spherical** particles, particles embedded in **disordered environment** (e.g. tissue)
- goal: **micromanipulation** in **complex scattering environments** using **wavefront shaping**



- strategy: exploiting the information stored in the system's **scattering matrix** with the **Generalized Wigner-Smith operator**[2,3]

Scattering Matrix and Wigner-Smith Operator

$$S = \begin{pmatrix} r & t' \\ t & r' \end{pmatrix}$$

r, r'...reflection matrices

t, t'...transmission matrices

scattering matrix connects incoming and outgoing channels

Wigner & Smith: **duration** of scattering event from **frequency derivate** of **scattering phase**[4,5]

e.g.: $t_{mn} = |t_{mn}| e^{i\varphi^t_{mn}} \rightarrow \tau = \frac{d\varphi^t_{mn}}{d\omega}$

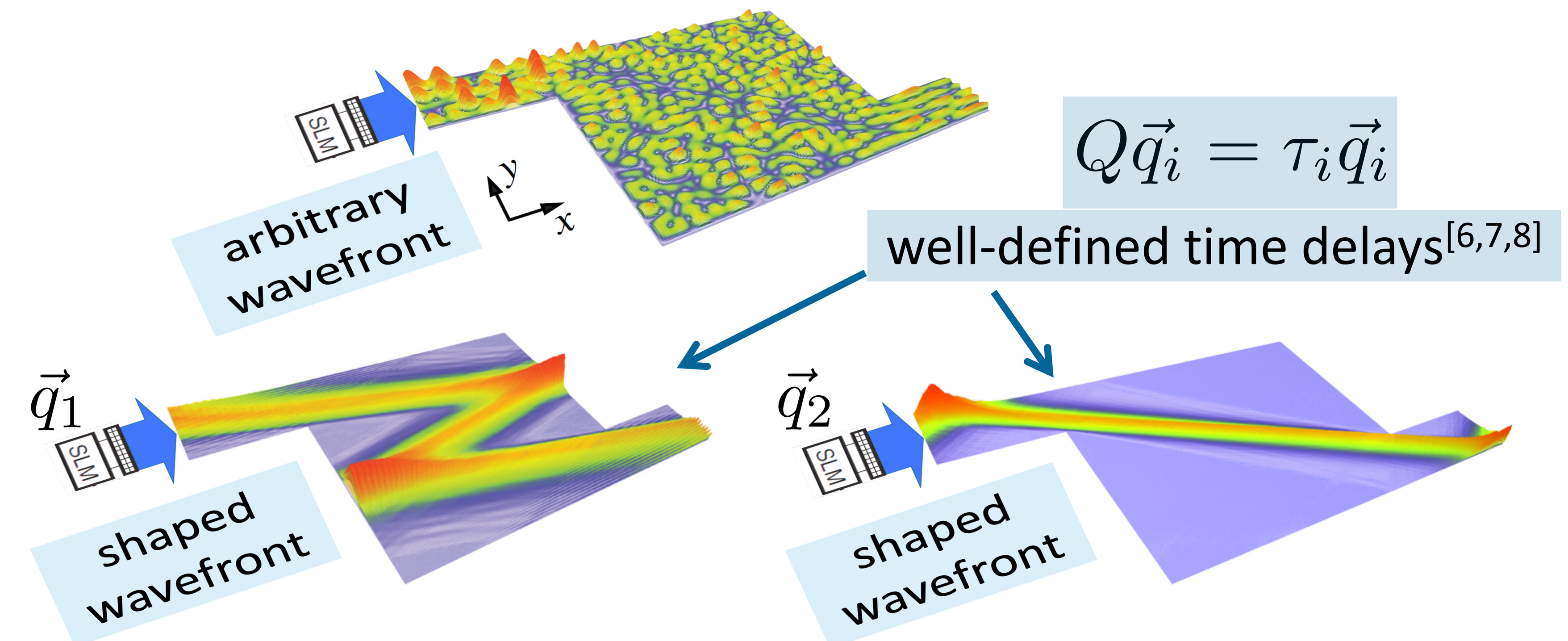
delay in transmission due to scattering

$$Q = -iS^{-1}(\omega)\frac{\mathrm{d}S(\omega)}{\mathrm{d}\omega}$$

Wigner-Smith time delay operator

$$Q\vec{q}_i = \tau_i \vec{q}_i$$

well-defined time delays[6,7,8]



Generalized Wigner-Smith Operator

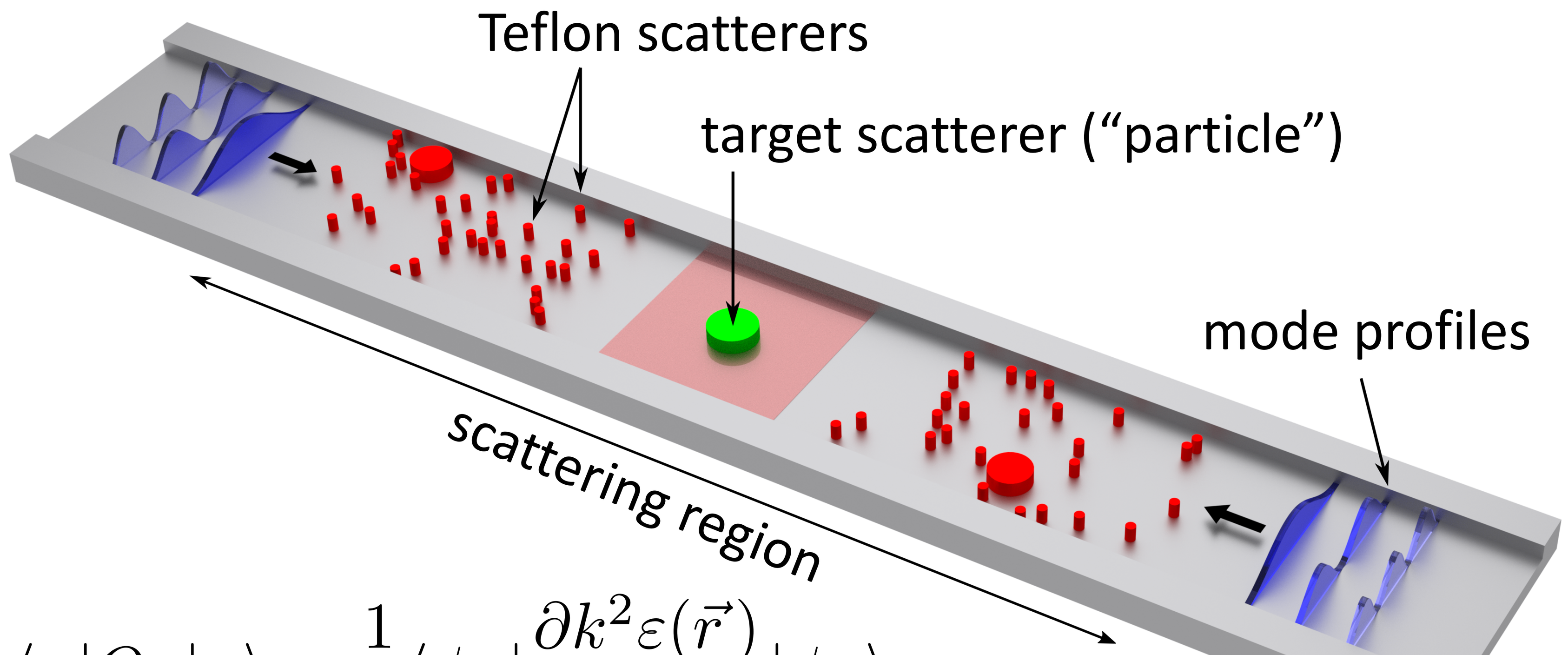
$$Q = -iS^{-1}(\omega)\frac{\mathrm{d}S(\omega)}{\mathrm{d}\omega} \rightarrow$$ eigenvalue = well-defined time delay

$\omega \rightarrow \alpha$

$$Q_\alpha = -iS^{-1}(\alpha)\frac{\mathrm{d}S(\alpha)}{\mathrm{d}\alpha} \rightarrow$$ eigenvalue = well-defined "conj(α)"

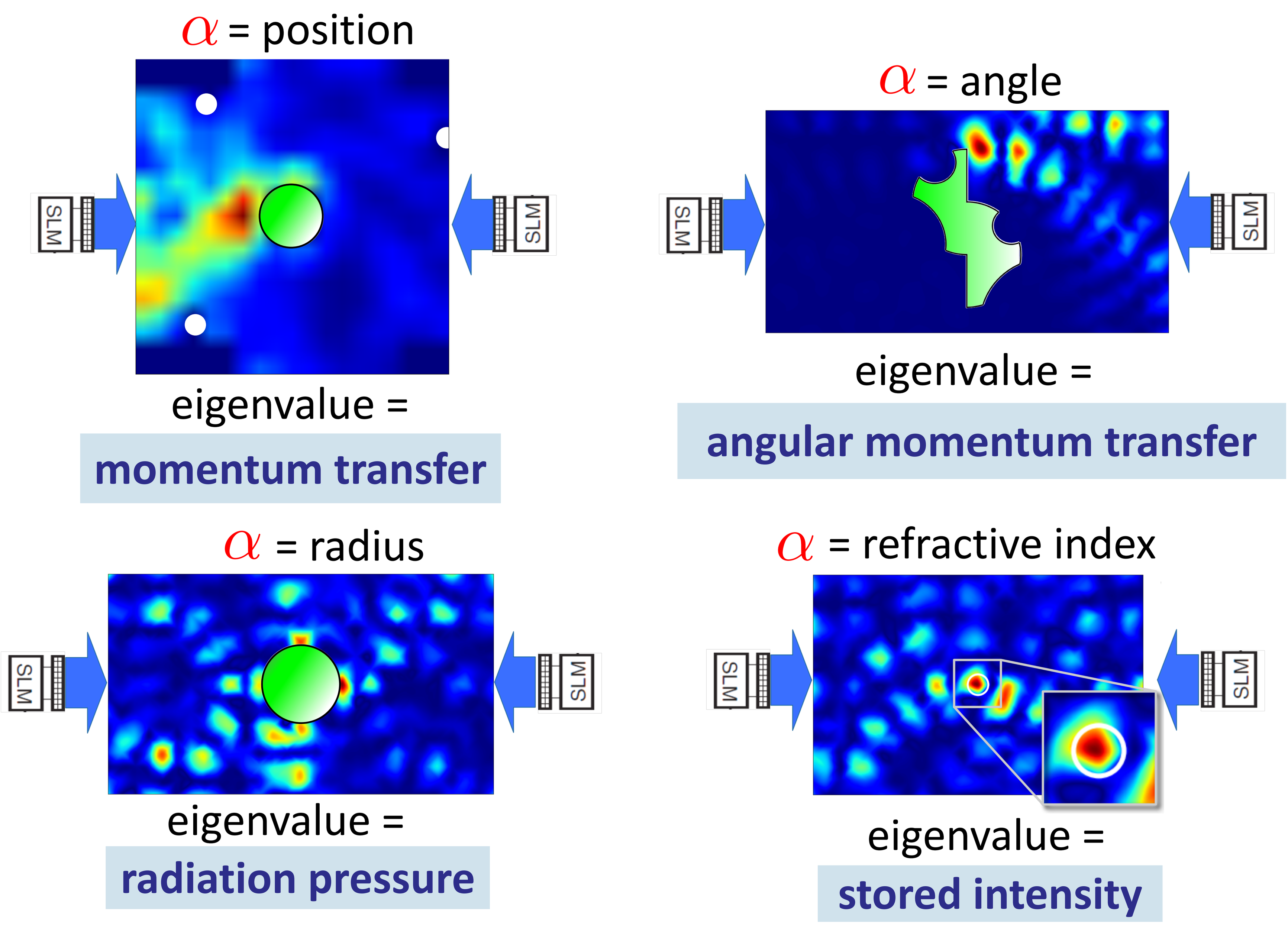
Experimental Results

- proof-of-principle experiment in **microwave waveguide**[2,3]



$$\langle\chi|Q_\alpha|\chi\rangle = \frac{1}{2}\langle\psi_\chi|\frac{\partial k^2\varepsilon(\vec{r})}{\partial\alpha}|\psi_\chi\rangle$$

- far-field information gives **access to near-field** of target particle



Summary

- states for transferring **momentum**, **angular momentum**, applying **radiation pressure** and storing **intensity**
- toolbox for **micro-manipulation** inside **complex media**
- **no near-field** information required as in Refs. [9,10]
- **optical realization** within reach

References

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