Opaque lenses

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Disclaimer

This document is an adaptation of slides used for a workshop presentation, and its main purpose is educational. Many details are presented in a simplified way.

Please refer to the original published papers (citations given on the slides) for full information on the scientific results and more complete reference to related work.
Coworkers

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Danang Birowosuto  - Postdoc (Now at NTT Japan)
Ivo Vellekoop  - Ph.D. Student (Now at CalTech)
Frerik van Beijnum  - M.Sc. Student (Now at U. Leiden)
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Sergey Skipetrov  - U. J. Fourier and CNRS Grenoble
Willem Vos  - Chair of COPS group
Outline

• Wavefront control of light
• Focusing *through* opaque materials
• Focusing *inside* opaque materials
• Universal optimal transmission
• Conclusion
Scattering

• A propagating light field has a large but finite number of degrees of freedom.

• Scattering is described by a matrix $S$.  

\[ S \]
Control scattering?

• If we know $S$, how well can we control the scattered light?

\[ "S^{-1}\]
How many matrix elements?

Number of degrees of freedom in a wavefront

\[ \text{DOF} = \text{# TE + TM modes in waveguide of same area} \]

\[ = 2 \frac{\text{Area}}{\text{Diffr. limited spot size}} \]

\[ = 2 \frac{\pi A}{\lambda^2} \]

\[ \text{# matrix elements} = (\text{DOF})^2 \]
Number of degrees of freedom in a light field

$(10 \ \mu m)^2 \ \ \ \ 1\ 600 \ \text{DOF;}$
$\ 2.5 \ 10^6 \ \text{matrix elements}$
$(5 \ \text{MB; one mp3 song})$

$(100 \ \mu m)^2 \ \ \ 160 \ 000 \ \text{DOF;}$
$\ 2.5 \ 10^{10} \ \text{matrix elements}$
$(50 \ \text{GB; a blu-ray disc})$

$(1 \ \text{mm})^2 \ \ \ 16 \ 000 \ 000 \ \text{DOF;}$
$\ 2.5 \ 10^{14} \ \text{matrix elements}$
$(500 \ \text{TB; monthly uploads to YouTube})$
Easiest approach: Feedback optimization

Spatial amplitude and phase modulation using commercial TN LCDs
Graphical representation

Maximize $E_b$
Phase of incident wavefront is conjugate of transmission matrix elements.

Global maximum before after

global maximum

Phase of incident wavefront is conjugate of transmission matrix elements.

global maximum

$\eta = \frac{\pi}{4}(N - 1) + 1$
Experimental setup

Sample: 10 µm layer of TiO2 pigment.
Light source: 633 nm HeNe laser.
Detection : 1 pixel of CCD camera.
Experimental results

measured transmission (normalized by average diffuse intensity)

Opaque objects focus light: Opaque lens

Intensity of focus

- Sample in focus
- Sample 100\,\mu m behind focus
- Theory (ideal situation)
- Theory (experimental conditions)
Opaque lenses

teeth (ex vivo)

daisy petals (fresh)

Scotch tape

porous semiconductor

paint (dry)

egg shell

daisy petals (fresh)

chicken breast (prepared)

Living tissue? (Cui, Mc. Dowell, Yang, Opt Expr. 2010)
Influence of scattering on focusing resolution

Traditional view:
Scattering degrades resolution

Acoustical work by Fink group:
Scattering can sometimes improve resolution

Does this work in optics?
Reference measurement: No scattering

D=2 mm

200 mm
No scattering: Diffraction limit of the glass lens

500 µm

Log I
Scattering sample at 100 mm

D=2 mm

Optimize intensity
With scattering: Smaller focus

500 µm

Scattering improves optical resolution

Log I
Focus size vs. distance

It’s the NA of the scattering sample that counts
(Theory, I. Freund, 1990)
(Acoustics: Fink group, PRL, 2003)
(Radio waves, Fink group, Science, 2007)
Opaque lens

Diagram:

(a) L1

(b) L2

CCD

D1

D2

f1

f2
Resolution and contrast

Normal lens / adaptive optics:
Wavefront error deteriorates focus size

Opaque lens:
Wavefront error scattered into background
(deteriorates focus contrast)
Focus size unaffected.
Wave transport and Random Matrices
Two regimes of wave transport

Waveguide geometry
Fixed number of propagating modes. Losses and leaks under control.

Open geometry
Real-world case. Most intensity leaks out of system.
Transport in lossless waveguide

The random sample is modeled as a waveguide with disorder.

Transmission matrix $t_{ab}$: coupling between $2\pi (HW)/\lambda^2$ channels, on left and right sides of the waveguide. We look for the eigenvalues of $tt^\dagger$

Strong parallels exist with transport of electrons (Anderson, John, Pendry, Beenakker, Soukoulis)
What happens to the matrix $t$ when we add a thin disordered slice to the sample?

Thin slice has transmission matrix close to unity. Eigenvalues only slightly perturbed: $\tau \rightarrow \tau + \delta\tau$

“Brownian motion of eigenvalues”
Bimodal transparency distribution

- Dorokhov, Mello, Perreyra, Kumar: DMPK distribution of eigenvalues (1980s).

\[ P(\tau^2) \propto \frac{1}{\tau^2 \sqrt{1-\tau^2}} \]

Pendry (1990): “Maximal Fluctuations”

Many closed channels
Transparency eigenvalues 0

FEW open channels
Numerical example

Transmission eigenvalue

2D waveguide width 75 λ
Numerical example

Transmission eigenvalue

2D waveguide width 75 $\lambda$
Numerical example

Transmission eigenvalue

2D waveguide width 75 \( \lambda \)
Numerical example

Transmission eigenvalue

2D waveguide
width 75 \lambda
Numerical example

Transmission eigenvalue

#

0.2 0.4 0.6 0.8 1

20
40
60
80

10. l

Transmission eigenvalue
How about the open geometry

Same as closed geometry, but we are not observing all of the input/output channels.

We look at a submatrix of $T$.

Famous result by Marchenko & Pastur:
Singular values of a small submatrix have quarter circle distribution.
Full N x N matrix

Singular value \( \lambda \)
$N/2 \times N/2$

Histogram of singular values $\lambda$: The histogram shows the distribution of singular values with a decreasing trend from left to right. The x-axis represents the singular value $\lambda$, and the y-axis represents the frequency or count of occurrences. The peaks at $\lambda = 0.2$, $\lambda = 0.4$, $\lambda = 0.6$, and $\lambda = 0.6$ are labeled with $P$. The singular values decrease as we move to the right on the x-axis.
N/10 x N/10

Quarter-circle distribution
Characteristic of open system
As measured by
Popoff et al., PRL 104, 2010
Towards perfect wavefronts

Perfect wavefront control:

- control all $2\pi A/\lambda^2$ incident modes
- Power in focus of order integrated background
- Light transmission strongly modified
Conservation of Energy

• If we optimize and make a focus:

If open channels not present:
Background transmission stays the same.
(all speckles uncorrelated)

If open channels present:
Background transmission grows
(Intensity is moved into open channels)
Setup for perfect wavefront control

– 2 polarizations
– High NA
– Small sample area
Before optimization
After optimization
Before and After

Experimental confirmation: Open channels are present

Optimal transmission

Transmission of a perfect phase conjugate wavefront

\[ T_\phi = \langle t^4 \rangle / \langle t^2 \rangle \]

2/3 for bimodal distribution,
2\langle T \rangle for quarter circle.

However, wavefront is not perfect.
The focus intensity is a measure for its quality.

Degree of control =
(Measured Intensity in focus)/(Ideal intensity)
= (# controlled DOF)/ (# total DOF)
More control, more transmission

Line extrapolates to \( T=0.64(7) \)

We find 0.67(17) for thicker samples

Direct evidence for bimodal distribution of transmission coefficients
Focusing *inside* opaque materials
Focusing inside

• First method to accomplish this!
• Use fluorescent probe particle for feedback.
First focusing deep in turbid material

Fluorescence from embedded 300 nm sphere

Deep focussing

Depth of sphere (mean free path)

Intensity relative to diffuse background

Depth of sphere (µm)

- Wavefront shaping
- Ballistic intensity (assuming all geometric aberrations are corrected)
New development

What is the size of the focus?

1 µm
What is the size of the focus?

Spot too small for our microscope

Infer spot size from ratio of excitation and emission enhancements

Blue lines: assume spot is optimally concentrated

Enhancements equal:
Probe size about focus size

Probe radius = 80 nm

Probe radius = 150 nm

Blue lines: assume spot is optimally concentrated
Fluctuations of emission rate

Experiment: Birowosuto, Skipetrov, Vos, Mosk, PRL 2010 (accepted)

C0 fluctuation predicted by B. Shapiro (PRL 1999)

Experiment: Birowosuto, Skipetrov, Vos, Mosk, PRL 2010 (accepted)
Vacancies for Ph.D students!

• New method for bringing light to a focus
  – Focus light through variety of materials
  – Focus light deep inside opaque objects
  – Universal transmission observed
  – Improved focusing observed
  – Fluctuations of LDOS observed

cops.tnw.utwente.nl for all our papers and recent M.Sc/Ph.D. theses
Related work emerging in several groups:

C.H. Yang (CalTech), presented at FiO 2009
K. Dholakia (St. Andrews), presented at SPIE OP 2009