OPTICAL IMAGING IN RANDOM MEDIA: FROM SURGERY TO WAVE MASTERING

Sylvain GIGAN, Sébastien POPOFF, Jonas BINDING & A. Claude BOCCARA

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OPTICAL IMAGING IN RANDOM MEDIA: FROM SURGERY TO WAVE MASTERING

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CARGESE JULY 12-15th 2010
Summer School "Mesoscopic
Physics in Complex Media"

What is Institut Langevin? Where is it ?

Paul Langevin :

Scientist (Langevin Equation)

+

Inventor of Sonar
Head of ESPCI for 20 year

Wave propagation and manipulation...

All waves!

(80 people, 30 permanent researchers)

Started January 2009

Optics

Acoustics

electromagnetism

biomedical

fundamental

Complex media

IMAGINE AND IMAGING

Photosource: designspongeonline.com

Model portfolio image from the official site for America's Next Top Model.

OPTICAL IMAGING: WHICH SCALE?

Diffuse Optical Tomography
(UCL)

STED microtubules network
(Stefan Hell)

TWO IMAGING APPROACHES

Selection of ballistic photons

SLICING VIRTUALLY
THROUGH TISSUES

No more ballistic light: seeing through an opaque wall

The actors: transmission matrix

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Mathias FINK

Sylvain GIGAN

The inspirers

Allard MOSK

Ad LAGENDIK

Igo
VELECOOP

Optical Tomography

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TWO IMAGING APPROACHES

Selection of ballistic photons

SLICING VIRTUALLY
THROUGH TISSUES

No more ballistic light:
seeing through an opaque wall

Selection of ballistic photons: why?

Intra operative diagnostic

**FAST DIAGNOSTIC
15' FEEDBACK**

**SLICING AND DETAILED ANALYSIS
1 TO 2 WEEKS FEEDBACK**

A POSSIBLE STRATEGY

EXPECTED BENEFITS

- Reduction of patients pain
- Reduction of the cancer hospitals delays
- Reduction of the health costs

- Complementary non contact and non destructive diagnostics only
- The “gold standard” (pathologist’s slices) analysis is still going on

In depth optical sectioning and pathology:

RPE: retinal pigmented epithelium. PRL: photoreceptor layer. ONL: outer nuclear layer. OPL: outer plexiform layer. INL: inner nuclear layer. IPL: inner plexiform layer. GCL: ganglion cell layer. NFL: nerve fiber layer.

In depth optical sectioning and pathology:

In depth optical sectioning and pathology:

Traditional
Histology

Skin layers

Muscle

Perichondrium

Cartilage

Perichondrium

Full Field OCT image

500 μm

3D rendering

OPTICAL COHERENCE TOMOGRAPHY: SELECTING BALISTIC PHOTONS

Balistic Photon Selection

OCT = optical echography

Fujimoto et al.

Ultrasound is replaced by light

Measurement of the amplitude and the travel time of
backscattered light

Low coherence interferometry

Selection of ballistic photons using low coherence interferometry

Figure 7.10 Fiber optic Michelson interferometer. Optical coherence tomography has the advantage that it uses many components and techniques from photonics. This schematic shows a Michelson interferometer with a circulator for dual-balanced detection. This configuration adds the heterodyne signal from the interference of the sample and reference arms and subtracts excess noise from the light source.

J.Fujimoto MIT

Image of the retina

Figure 7.13 Comparison of standard and ultrahigh-resolution OCT images of the normal human retina. The axial resolution is 10 μm using an SLD light source and 3 μm using a femtosecond laser light source. The ultrahigh-resolution OCT image enables visualization of all major retinal layers (Drexler et al., 2001).

Image of the retina

webvision.umh.es/webvision/ClinicalERG.htm

Optical coherence tomography (OCT) images of the patient's normal macula and of the retina in the other eye with the macular detachment.

Principle of full field OCT

SENSITIVITY $\approx 90\text{dB}$ (1 backscattered photon over 1 billion)

RESOLUTION $\approx 1\mu\text{m}$ in all directions

Acquisition of the images

Tomographic Images *en face* (XY)

❖ Axial Resolution of Full Field OCT : Experiment

S. Boppart and col.
**Optical Biopsy of Lymph Node
Morphology using Optical
Coherence Tomography**
*Technology in Cancer Research &
Treatment ISSN 1533-0346
Volume 4, Number 5, October
(2005) ©Adenine Press (2005)*

Lymphatic channels

FFOCT
500μm

Lymph Nodes
ex vivo

Benign and Malignant Lesions in the Human Breast Depicted with Ultrahigh Resolution and Three- dimensional Optical Coherence Tomography

J. Fujimoto and col.

Radiology 2007; 244:865– 874

with dynamic refocusing

FFOCT
500μm

MILK DUCTS

Supporting tissue

Growing
secreting cells of
the membrane

Figure 6: (a, b) OCT images of ductal hyperplasia. On b, magnified image of ductal region in inset on a shows highly scattering projections into the ductal lumen corresponding to hyperplastic epithelium or fibro-vascular core (arrowheads). (c, d) Histologic specimens corresponding to OCT images. (Hematoxylin-eosin stain; original magnification, $\times 40$ in c and $\times 100$ in d.)

Histological section of normal large intestinal mucosa

FULL FIELD OCT

HISTOLOGY

NORMAL COLON

Figure 7.21 Ultrahigh-resolution OCT image of normal colon ex vivo (left) and comparison histology (right). Mucosa (M) is clearly delineated from underlying submucosa (SM) by a scattering band corresponding to the thin muscularis mucosa (arrowheads). The submucosa is visible as a less optically scattering layer. Images were acquired with 4.5- μm axial and 11- μm transverse resolution at a 1.26- μm wavelength (Hsiung et al., 2005).

NORMAL COLON

ULTRAHIGH RESOLUTION OCT

HISTOLOGY

**FULL-FIELD OCT (FFOCT) :
FROM BENCH TO THE
OPERATING ROOM**

Human colon – fixed tissue

FFOCT results are comparable to traditional histology

← 5 mm →

FF OCT
Few minutes

X 20

X 100

Traditional histology
Several days

Human colon – fixed tissue

FFOCT results are comparable to traditional histology

Histology
Several days

FF-OCT
Few minutes

LLTech FF-OCT
Few minutes

Histology
Several days

ILEON 3D Imaging enable virtual navigation at a cellular level into the analyzed tissue

3R rendering of human intestine

The 3D viewer allows to virtually navigate into the volume

Crohn's disease structure not visible at the surface

Fat cells

ILEON 3D Imaging enable virtual navigation at a cellular level into the analyzed tissue

Human colon – fixed tissue

FFOCT Zoom on chosen parts

BREAST CANCER SURGERY

FFOCT PICTURES ARE COMPARABLE TO HISTOLOGY

Breast Histology

Identification of the milk duct structures

Breast cancer surgery

Milk Duct Structures

Milk Duct End

Fat Cells

Light-CT (10x 0.3NA)

Histology

ANIMAL MODEL: IN VIVO IMAGING OF RATS BRAIN

Rat brain
Objective:40x
Field of view
120x120 μm^2 and 260x260 μm^2

Col. L.Bourdieu's group ENS

RAT BRAIN: BLOOD CIRCULATION

TWO IMAGING APPROACHES

No more ballistic light:
seeing through an opaque wall

An inspiring experiment !

Optimization

Fig. 1. (Color online) Design wave is focused on a disorder
tern is transmitted. (b)
is shaped so that scatter:
defined target

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tern is transmitted. (b) The v
is shaped so that scattering r
defined target.

How does it work?

One speckle spot :

- Interference from many different path with random phases
- All input modes contribute!
- It is possible to put these modes in phase to obtain constructive interference

Wavefront control device

Deformable mirrors : 10-100 actuators typical - course : 10-20 microns – kHz
Spatial Light Modulators : 1 million pixel typical – course : 1 microns typical – 50Hz

Complex material = a LOT of degrees of freedom
 SLM is (so far) more adapted

The scattering matrix

Our system of study: A thick (opaque) layer of ZnO on a slab

- Very stable (stationary diffuser, stable speckle figure)
- Completely disordered, in the multiple scattering regime
- Linear, open system**

A natural formalism: the scattering matrix

Link the input to the output **fields** of the system

Scattering matrix S

The transmission matrix (TM)
can be measured with a CCD and a SLM!

Experimental setup

$N=256$
macropixels/
modes

SLM
 $N=256$
macropixels
/modes

Iterative focusing in a time N (Allard Mosk Group)

We have been able to measure the transmission matrix K in $4N$ steps

S. Popoff et al, Phys. Rev. Lett. 104, 100601 (2010)

Limitations

- The TM measurements takes a lot of steps ($4N_{\text{input}}$)
- Current limitation is the refresh rate of the SLM (50Hz), N_{output} on the CCD is not a limitation.
- Measuring the TM takes approx. 2-3 minutes for 256 pixels
- The TM can be used as long as the medium is stable (speckle stationnary). Paint : >1 hour , biological sample : <1ms !!!

Nonetheless, we can do a number of things

Exploiting K_{obs} : focusing

Can K tell us what input will give a given output?

YES:

interpretation : **phase-conjugation**

With a phase-only SLM, we have to send

(Full resolution)

Initial speckle

One point focusing

Multiple point focusing

Ability to focus on any, or many points **in one step**.

Similar SNR expected as for iterative focusing (here SNR=54 for $N=256$ pixels)

The transmission modes

K is a $N \times M$ complex matrix, not hermitian

A singular value decomposition (SVD) consists in writing $K = U \Lambda V$,

where U and V are *unitary matrices*

Λ is a *diagonal* matrix whose nonzero elements λ_i **are called the singular values of K .**

The distribution of singular values $\rho(\lambda)$ is a relevant observable of **transport** :

- The λ_i corresponds to the **transmission values**
- The corresponding U_i and V_i corresponds to the **input and output eigenvectors**

Can we better exploit these channels for imaging ?

Why not use the obvious (K^{-1}) ?

Because noise will degrade the reconstruction for the small singular values of K .

(Well-known fact in inverse problems)

There is a solution to this problem of reconstruction in presence of noise, used in telecommunication and in Optical tomography for instance. The optimal operator is :

Renormalization

Without noise :

(inversion is optimal)

With a lot of noise :

(phase conjugation is very resilient to noise)

Experimental setup

Image transmission

We can tune this parameter

Can we avoid averaging?

Increasing the number of detection pixel

Singular value distribution for increasing N_{pixel}

- Averaging for free
- Less sensitive to noise

Results:

No need to average for >90% fidelity

Does not increase measurement time

Even inversion work

USING THE MEMORY EFFECT: IMAGING WITHOUT TRANSFER MATRIX

PRINCIPLE OF THE EXPERIMENT:

(a) A turbid layer blocks a fluorescent structure from sight; all incident light is scattered. (b) By use of interferometric focusing (e.g., phase conjugation or wavefront shaping), scattered light is made to focus through the layer. (c) Imaging: the focus follows rotations of the incident beam. The hidden structure is imaged by scanning the focus. (d) Experimental setup. A laser beam is raster scanned, and its wavefront is shaped with a spatial light modulator (SLM). Dotted lines are conjugate planes. For ease of view, the SLM is drawn as a transmissive device, and folding mirrors are omitted.

Scattered light fluorescence microscopy: imaging through turbid layers

Ivo M. Vellekoop^{1,*} and Christof M. Aegerter^{1,2}

Fig. 2. (Color online) Dense cluster of 200 nm diameter fluorescent beads. (a) Seen directly (from the back of the sample) with a wide-field fluorescence microscope, no scattering layer between the structure and the microscope. (b) Seen through the 5.1-μm-thick scattering layer with a wide-field fluorescence microscope. The structure lies 1 mm below the layer. Only a diffuse spot, much larger than the fluorescent structure, is visible. Square box, area scanned with the SLF microscope. (c) Seen through the scattering layer with the SLF microscope. The structure is clearly visible at a high resolution. The image was mirrored for ease of comparison with (a).

Conclusions

Selecting ballistic photons allows a useful “slicing” of random media up to about ten of mean free path (100 dB). Limitations must be understood:

- 1) Influence of the multiscattered photons detected by the coherent gate
- 2) Influence of the large scales heterogeneities (coupling with adaptive optics)

Measurement of the the transmission matrix of a multiple scattering medium.

- 1) not so difficult nor slow even with current technology
- 2) An operative tool to manipulate light :
 - Application to focusing
 - Application to imaging, beyond phase conjugation
- 3) An important tool to study complex material experimentally
 - Demonstration of a universal behavior or RMT : the quarter circle law
 - fill a gap between theory and experiments

Perspectives:

More applications!

More fundamental measurements!

Any critic or suggestion welcome!