Turbidity suppression by optical phase conjugation (TSOPC)

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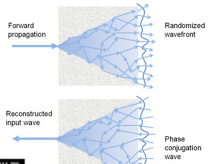
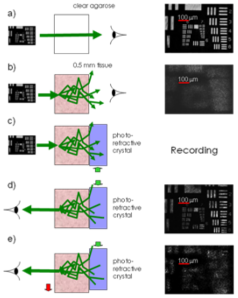
Abstract:

Elastic light scattering is the dominant process through which light is attenuated as it travels through biological tissue. This sets a limit for optical imaging techniques in terms of penetration depth, and information is lost due to multiple scattering. Here we show that information passing through a scattering media can be recovered using a technique termed turbidity suppression through optical phase conjugation (TSOPC) [1]. Taking advantage of the fact that elastic light scattering is deterministic, holographic methods are used to 'time reverse' a scattered wavefront, forcing it to retrace its path through the scattering media. We demonstrate this technique in both phantoms and biological tissue samples, and show that that this effect can work even for a large number (hundreds) of scattering events. Additionally, we motivate this technique as a potential metric for tissue health based on signal degradation due to cellular motions. A challenge for biomedical applications of TSOPC is that the conventional nonlinear optics based methods provide fairly limited OPC reflectivity. Inspired by acoustic time reversal techniques, we have recently developed a digital OPC method (DOPC) that can in principle provide unlimited OPC reflectivity [2].

Motivation



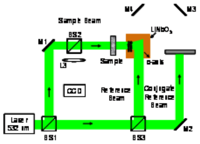
Elastic light scattering is the dominant process through which wavefront is randomized. Despite the apparent randomness, elastic scattering of light is a deterministic and time reversible process. Using phase conjugation, we can effectively time reverse the scattering process and undo the distortion caused by scattering.



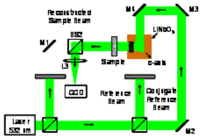
Previous work

a) An image-bearing light field can be clearly imaged through a clear medium. b) A 0.5 mm thick tissue significantly scatter and diffuse the original light field. c) We record the light field on a photorefractive crystal by interfering the transmission with a reference light field. d) We can play back a time reversed or OPC field by reading out the recording with an appropriate readout field. The transmission accurately reconstructs the original input field. e) When we shift the tissue during the playback process, the time-reversed light field would no longer be able to retrace their way through the tissue and reconstruction disappears.

Experimental method

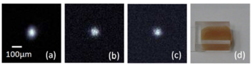


- 532 nm CW laser source.
- A collimated beam illuminates the sample (~20 mW).
- The scattered wavefront is recorded in a $LiNbO_3$ crystal through interference with a reference beam (~20 mW).
- The sample is located close to the crystal (mm's) to create a large collection angle.
- Exposure time of 30 seconds.



- A phase conjugate reference beam (~ 2 mW) is used to play back the scattered wavefront.
- The phase conjugate beam retraces its trajectory through the scattering media, and is collimated upon exiting the sample.
- The reconstructed beam is then focused onto a CCD and recorded using a variable integration time (0.25 ms – 1 s).
- The strength of the reconstructed beam is a measure of the efficiency of our TSOPC technique.

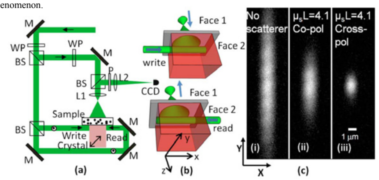
Demonstration in thick tissues



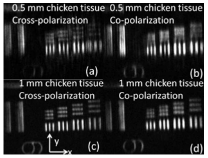
OPC images reconstructed through 3 mm (a), 6 mm (b), and 10 mm (c) thick chicken breast tissues. (d) Photo of the 10 mm thick tissue.

Spatial resolution vs. turbidity

Light transmitted through thicker tissues will spread to a larger area. Given the finite size of the OPC mirror, a smaller portion of the transmitted light can be phase conjugated. Will this deteriorate the spatial resolution? We implemented the following experiment [3] to investigate this phenomenon.

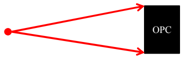


(a) Experimental setup for the polarization gated OPC. M, mirror; BS, beam splitter; P, polarizer; WP, half wave plate (532nm); L1, L2, lenses. The concentric dark ring and dot represents the vertical polarization of the laser beams. The dark arrow on the crystal represents the direction of the c-axis of the crystal. (b) 3D illustration of the recording volume. (c) OPC images reconstructed without scatterers (i) between the point source and the photorefractive crystal and through 1mm thick tissue phantoms of μ_sL=4.1 with the input light polarization parallel (ii) and perpendicular (iii) to the writing beam polarization.

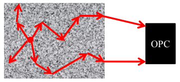


Use OPC to reconstruct a USAF target through 0.5 mm and 1 mm thick tissues with co-polarization recording and cross-polarization recording. The results confirm that random scattering can help increase the spatial resolution in TSOPC

An intuitive explanation



Without scattering, resolution determined by OPC mirror NA

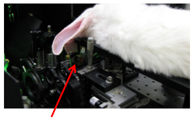


With scattering, resolution determined by correlation length, which is ~λ/2 in sufficiently thick media

TSOPC in live animal

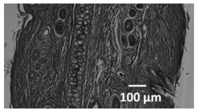
A challenge for *in vivo* applications is that the tissue varies over time, which may perturb the TSOPC process. We performed TSOPC experiments on a live rabbit to evaluate the speed of the perturbation process. [4]

Photo of the experiment

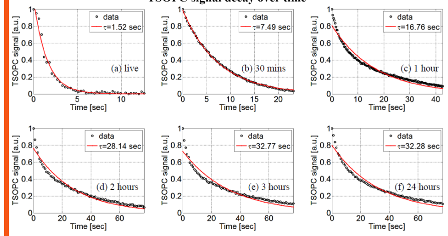


Photorefractive crystal

Histology of the rabbit ear



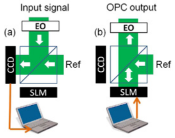
TSOPC signal decay over time



(a-f) TSOPC signal decay measured while the rabbit is alive and at 0.5, 1, 2, 3, 24 hours after the ear is excised. The data is fitted with an exponential function (red line). This set of measurements suggest that the dominant perturbation to TSOPC comes from the heart beat of the animal.

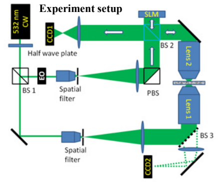
Digital optical phase conjugation (DOPC)

A challenge of using conventional nonlinear optics based OPC system for biomedical applications is that the OPC reflectivity is fairly limited. We have implemented a digital OPC system that can in principle provide unlimited adjustable OPC reflectivity.

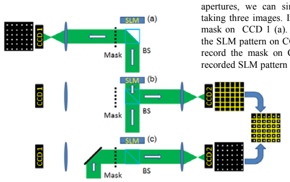


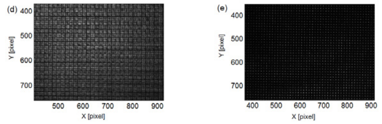
The design of DOPC is inspired by the time reversal experiment, in which a sound transducer is used both as a sensor and an actuator. We optically combine the SLM with a CCD camera such that the two devices form virtual images.

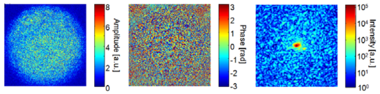
Experiment setup



A critical step is to accurately map the SLM pixels to the CCD pixels. Using a mask with a matrix of apertures, we can simply perform the mapping by taking three images. In the first image, we record the mask on CCD 1 (a). In the second image, we record the SLM pattern on CCD 2 (b). In the third image, we record the mask on CCD 2 (c). (d) and (e) are the recorded SLM pattern and the image of the mask.



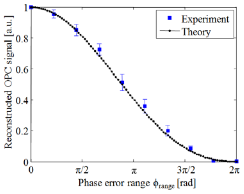




Measured amplitude and phase profile of the incident wave, and the reconstructed beam profile.

Phase error tolerance study

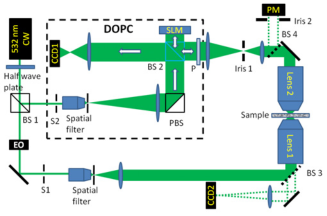
We can reasonably expect that the effectiveness of OPC through a scattering medium to reconstruct an initial input field should depend on the accuracy by which the phase conjugate field is produced. The exact relationship between fidelity and reconstruction efficiency is important and relevant as it can guide us in making informed design choices in OPC-based applications. However, this relationship is difficult to study experimentally with conventional OPC methods as it is difficult to controllably introduce errors into the phase conjugate fields. The DOPC system affords us an easy and well controllable means for introducing known phase errors into the OPC wavefront. We can simply add the desired phase shifts into the DOPC wavefront that the SLM generates.



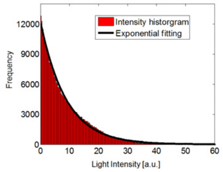
Theoretical calculation and experimental measurements of the reconstructed OPC signal dependence on the amount of phase error.

Phase-only OPC vs. full OPC

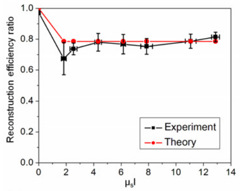
A full OPC wave contains both amplitude and phase information, which requires two sets of degrees of freedom to fully describe or encode. To generate a full OPC wave with spatial light modulators (SLM), we would need to perform both amplitude modulation and phase modulation. Experimentally, it will be much easier if we can discard one set of degrees of freedom. In this way, we can reduce the required information processing to half and potentially speed up the playback rate. Experimentally, such a system would also be simpler to implement. Here we compare the reconstruction efficiency of phase-only OPC to full OPC.



Experiment setup. The light source is a solid state CW laser at 532 nm (Spectral Physics, Excelsior). BS1-4=beam splitters, S1,2=shutters, CCD 1,2=CCD camera, PBS=polarization beam splitter, P=vertically polarized polarizer EO=electro-optic phase modulator, Lens 1,2=NA 1.3 oil immersion objectives, PM=power meter, DOPC=digital optical phase conjugation system.



Despite the apparent randomness, the intensity of the light transmitted through a random scattering medium obeys a negative exponential distribution. Here we show the measured intensity histogram and its exponential fitting. Based on this statistic distribution, we predict that the reconstruction efficiency of phase-only OPC to full OPC is π/4.



Both the theoretical analysis and the experimental study suggest that the reconstruction ratio of phase-only OPC to full OPC in sufficiently random media approaches π/4

Conclusion:

- OPC is a robust method of forming focus through turbid media
- DOPC can provide unlimited phase conjugation reflectivity, suitable for biomedical applications

Potential applications:

- Molecular imaging in deep tissues
- Enable advanced microscopy in complex samples
- Focus light onto targets embedded in tissues.

References:

1. Z. Yaqoob, D. Psaltis, M. S. Feld, and C. Yang, "Optical phase conjugation for turbidity suppression in biological samples," Nat. Photonics 2, 110-115 (2008).
2. M. Cui and C. Yang, "Implementation of a digital optical phase conjugation system and its application to study the robustness of turbidity suppression by phase conjugation," Opt. Express 18, 3444-3455 (2010).
3. M. Cui, E. J. McDowell, and C. H. Yang, "Observation of polarization-gate based reconstruction quality improvement during the process of turbidity suppression by optical phase conjugation," Applied Physics Letters 95(2009).
4. M. Cui, E. J. McDowell, and C. Yang, "An in vivo study of turbidity suppression by optical phase conjugation (TSOPC) on rabbit ear," Opt. Express 18, 25-30 (2010).

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