OCT-guided wavefront shaping for non-invasive depth-selective focusing

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We demonstrate optical wavefront shaping combined with complex-valued OCT signal acquisition. Shaping the wavefront incident to a strongly scattering sample is demonstrated to enhance the OCT signal received from a point-like target within the sample, eventually focusing light to that position. By stitching multiple point-optimized OCT scans a fully optimized depth-scan is recovered and the sample structure behind a scattering layer can be revealed.

1 Introduction

Optical Coherence Tomography (OCT) allows for three-dimensional optical imaging based on time-of-flight sensitive detection of light backscattered from a sample through coherence gating. Due to the non-invasive nature of the technique, its high axial and lateral resolution and high imaging speed, OCT has become a significant technique for medical imaging e.g. in ophtalmology. Strong scattering in samples such as human skin or inhomogeneous tissue strongly reduces the OCT signal which can be acquired, however, typically limiting the penetration depth in such samples to a few millimetres.

Due to the deterministic nature of scattering, the optical intensity within or behind a turbid medium can be locally enhanced by shaping the optical wavefront incident to the sample [1]. Since the OCT signal acquired depends on the intensity within the optical detection volume, wavefront shaping potentially allows to enhance the acquired signal and imaging depth in strongly scattering environments.

In this paper we demonstrate OCT signal enhancement based on iterative optical wavefront shaping and point out imaging applications.

2 Methods

The experimental aparatus is based on a Linnik-type interferometer fed by a broadband light source (SLD830S-A10, Thorlabs, USA). Light backscattered from a sample and from the reference arm is coupled to a single-mode optical fibre and analysed by a spectrometer (SR500i with DV420A-OE camera, Andor, UK) for OCT signal acquisition.

A spatial light modulator (SLM) (HEO1080P with NIR11 display, Holoeye, GER) which is illuminated using a beamsplitter cube shapes the optical wavefront incident to the OCT system. By using the beam which bypasses the SLM at the beamsplitter a static reference beam for OCT signal acquisition is created and wavefront shaping at the SLM, thus, affects the sample arm of the OCT system only [2].

By displaying a uniform pattern to the SLM a constant phaseshift is applied to the interferometer sample arm. Through sequential application of defined phaseshifts and recording of the acquired interference signals at the spectrometer, the complex valued spectral interferogram can be calculated through algorithms known from phase shifting interferometry. Calculating the inverse Fourier Transform from this complex valued interferogram yields an OCT depth scan with increased signal-to-noise ratio and greatly reduced imaging artefacts [3].

For OCT-based wavefront shaping a fixed target, which corresponds to a rectangular depth-window from a single OCT depth-scan, is selected from the 3-D scan volume. A genetic algorithm [4] is then used to find an optimized pattern applied to the SLM which maximizes the signal retrieved from the target. For any pattern under test during the optimization procedure a constant phaseshift can be superimposed to allow for simultaneous complex-valued signal acquisition.

3 Results

We demonstrate OCT-based wavefront shaping with a layered scotch tape phantom. The layered structure is partially hidden under a sheet of lab tissue (Kimtech Science, Kimberly-Clark, USA) which is fixed with a top-layer of scotch tape. For complex-valued OCT signal acquisition a 4-step phase shifting algorithm is used which significantly reduces imaging artefacts as compared to conventional acquisition. Residual artefacts are an effect of imperfect phase modulation by the SLM.

A cross-sectional OCT scan taken at the sample's tissue edge with a flat wavefront applied to the SLM is illustrated in figure 1a. The OCT signal clearly reveals the sample's layered structure where no tissue is present. However, strong scattering at the tissue completely hides the signal received from the sample structure hidden behind.

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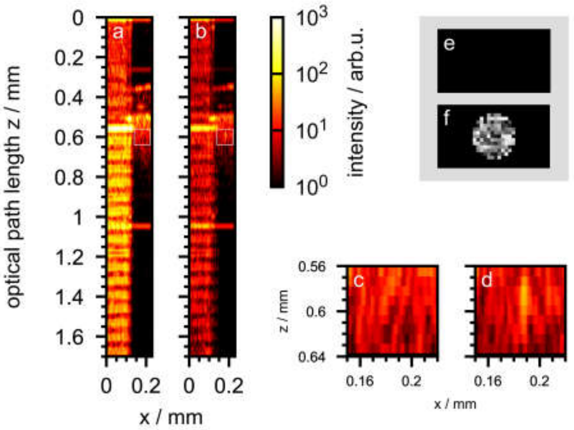

Fig. 1 Single-target focusing behind a scattering layer ***(a)*** *Cross-sectional scan with flat wavefront applied. To the right the layered scotch-tape phantom is obstructed by a sheet of scattering tissue hiding the sample structure behind.* ***(b)*** *Cross-sectional scan with optimized SLM pattern applied. The pattern was shaped for enhancement of the signal received from a point behind the scattering layer. The target position is centred in the white rectangles highlighted in a and b.* ***(c, d)*** *Magnification of the areas highlighted in a and b, respectively. The target for wavefront shaping is centred in the respective graphs.* ***(e)*** *SLM pattern applied for acquisition of a and c.* ***(f)*** *Optimized SLM pattern applied for acquisition of b and d.*

To demonstrate OCT-based wavefront shaping, a target position behind the scattering layer was arbitrarily chosen and a phase pattern applied by the SLM was searched to maximize the signal received from that target. A cross-sectional scan with the optimized pattern applied is illustrated in figure 1b. Application of the optimized wavefront reduces the OCT signal received from the non-scattering part of the sample while signal enhancement at the target position behind the scattering layer is observed. The effect of signal enhancement is strongly localized as is expected for wavefront shaping. A minor displacement of the observed signal maximum with respect to the supposed target position evident in figure 1d is an effect of mechanical drift of sample and scanning device used.

For image enhancement based on wavefront shaping, the target position behind the scattering layer was axially moved through the sample in increments of 20 µm. For each target position the wavefront incident to the sample was optimized and the resulting depth scan acquired individually. The signals received only from the target positions of each of the optimized scans were stitched to receive the fully-optimized depth scan illustrated in figure **??**. As compared to the signal acquired with a flat wavefront applied to the sample, wavefront shaping results in a significant signal increase when strong scattering is present and reveals the sample's layered structure hidden behind the scattering tissue.

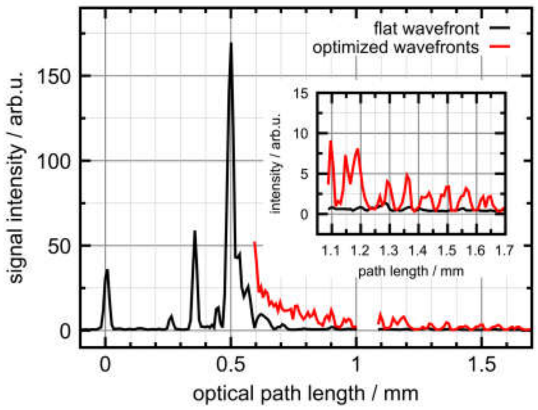

Fig. 2 Optimized depth-scan *Depth-scan acquired with a flat wavefront applied and scan received from stitching signals acquired after wavefront-shaping at different target depths. The scans were taken at the layered phantom covered by a scattering tissue. To account for the signal artefact present from 1,0 to 1,1 µm this interval is omitted.*

4 Conclusion

Wavefront shaping was demonstrated to locally increase the OCT signal received from a scattering sample. Since this signal depends on the optical intensity within the spatially confined OCT detection volume, the technique potentially allows for local intensity enhancement at this volume and, thus, non-invasive focusing inside of scattering media.

Scanning the target position through the sample volume potentially allows for depth-enhanced OCT imaging in scattering samples such as human skin. Due to its iterative nature, the application of wavefront shaping is limited by long optimization times, however, currently prohibiting imaging of living tissue. Utilization of faster devices for wavefront modulation combined with more efficient algorithms might be able to sufficiently speed up the process.

References

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