Fast wavefront manipulation for OCT signal enhancement

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Optical Coherence Tomography (OCT) is a valuable tool for medical diagnostics. The penetration depth in samples such as biological tissue is limited to the range of a few millimetres due to scattering, however. We demonstrate non-invasive acquisition of the reflection matrix which describes scattering at the turbid sample. The technique allows for selective enhancement of the received OCT signal.

1 Introduction

Optical Coherence Tomography (OCT) allows for non-invasive high resolution three dimensional optical imaging. The penetration depth in biological tissue such as the human skin is typically limited to the range of a few millimetres due to strong scattering at the sample. Hence, besides the potential of the technique the diagnostic use in clinical fields such as dermatology is limited.

Scattering of light is a deterministic process and, thus, the field inside of the sample as well as the backscattered field can be shaped by manipulating the field incident to the sample. Previous work demonstrated wavefront shaping to enhance the OCT signal received from a scattering sample, potentially increasing the signal-to-noise ratio as well as the penetration depth [1, 2].

We demonstrate the acquisition of the optical reflection matrix, which describes scattering at the sample, with a customized spectral domain OCT (SD-OCT) system. We further demonstrate enhancement of the OCT signal based on the above matrix.

2 Experimental procedure

The experimental device is based on our previous design which utilizes a liquid crystal spatial light manipulator (SLM) for wavefront control at the sample arm of a SD-OCT system [1]. We turned mirror M_1 (Fig. 1 in [1]) such that both the sample and the reference beam are reflected by one half of the SLM screen which, hence, can be utilized to shape the wavefront at both beams independently. The SLM is further used to apply a phase offset to either beam and to acquire the complex-valued OCT signal from phase shifting interferometry [1].

The optical reflection matrix describes the complex-valued relation between the field incident to the sample and the reflected field. Both fields may be described in terms of an orthogonal modal basis. In this case, the reflection matrix describes the relation between the amplitudes of the incident and the scattered modes [3, 4, 5]. For the system presented we consider the reflection matrix to yield the relation between the incident field and the resulting complex-valued OCT signal.

We use the SLM to create a set of orthogonal basis modes at the sample beam. For the data presented, we chose to implement a Hadamard basis [3]. In case a single isolated mode is applied to the sample the complex A-scan yields one row of the reflection matrix [3, 4, 5]. The full matrix is acquired by cycling through all modes. Once the matrix is acquired we chose an arbitrary target position within the range of the OCT scan and calculate the incident field which is expected to give rise to the signal at the target from optical phase conjugation [3, 4].

3 Results

We demonstrate the technique with a scattering sample consisting of multiple stacked polymer film layers (Parafilm M, Pechiney Plastic Packaging, USA) behind a single cover glass slide (compare [1]). Figure 1 illustrates the OCT signal acquired from that sample. The signal peak corresponding to the cover glass front reflection is observed at a depth of 0.2 mm. At depths below 0.5 mm reflections at the interfaces between the polymer layers are evident.

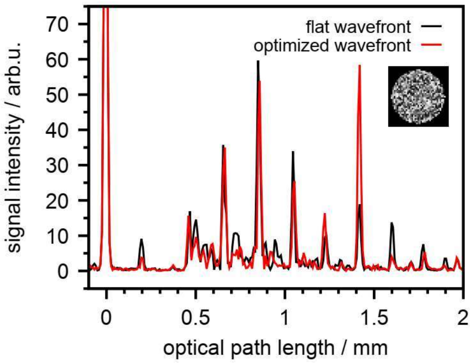

__Fig. 1 Single-point signal enhancement.__ A-scan taken with a wavefront optimized for a signal enhancement at a depth of 1.4 mm applied to the sample. The inset illustrates the corresponding pattern displayed at the SLM.

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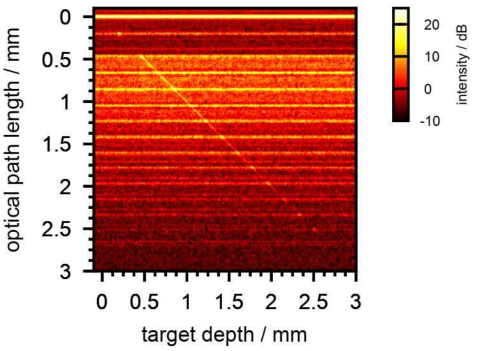

Fig. 2 Signal enhancement at different target depths. *Each column corresponds to one A-scan taken with a wavefront optimized for signal enhancement at the selected target depth.*

We acquired the reflection matrix for a set of 1024 independent modes and subsequently calculated the wavefront which is expected to result in an enhancement of the OCT signal received from the interface between the fifth and the sixth polymer layer. The A-scan taken after sample illumination with that wavefront (Fig. 1) features a strong signal enhancement at the supposed target. We repeated the experiment for a number of different target positions (Fig. 2). The corresponding wavefronts were calculated from the same reflection matrix. The clearly visible diagonal trace in Fig. 2 proves the selective enhancement of the OCT signal at the supposed target.

By taking the diagonal elements in Fig. 2 an OCT scan is recovered which results from signal enhancement at each depth position [2]. The resulting scan is illustrated in Fig. 3 and features a significant signal enhancement as compared to the conventional scan taken with a flat wavefront applied to the sample.

4 Discussion

The acquisition of the reflection matrix of a scattering sample allows to shape the OCT signal detected from the back scattered field by manipulating the wavefront incident to the sample, e.g. to selectively enhance the signal received from an arbitrarily chosen target depth. In general the efficiency of the technique depends on the number N of controlled modes incident to the sample [4], as does the acquisition time since the measurement of N complex-valued OCT signals is required.

The reflection matrix yields the dependence of the complete A-scan signal on the incident field. In contrast to iterative wavefront shaping, which requires one optimization process for signal enhancement at each target position [1], the data allows to calculate the incident field for a signal enhancement at an arbitrarily chosen target without further acquisition. A significant speed enhancement for the optimization of the full scan results.

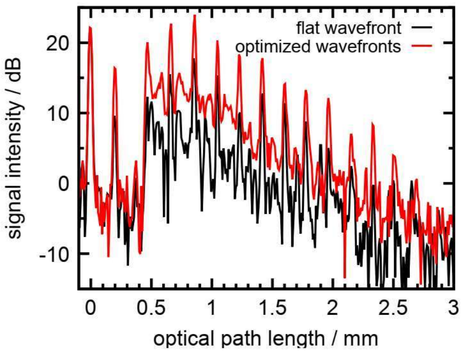

Fig. 3 In-target OCT signal. *The optimized OCT signal corresponds to the diagonal elements in Fig. 2.*

5 Conclusion

We demonstrated the acquisition of the depth-resolved optical reflection matrix and subsequent optical phase conjugation to selectively enhance the OCT signal from a scattering sample by manipulating the optical field incident to the sample. The technique lends itself for OCT signal and penetration depth enhancement when imaging strongly scattering media.

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