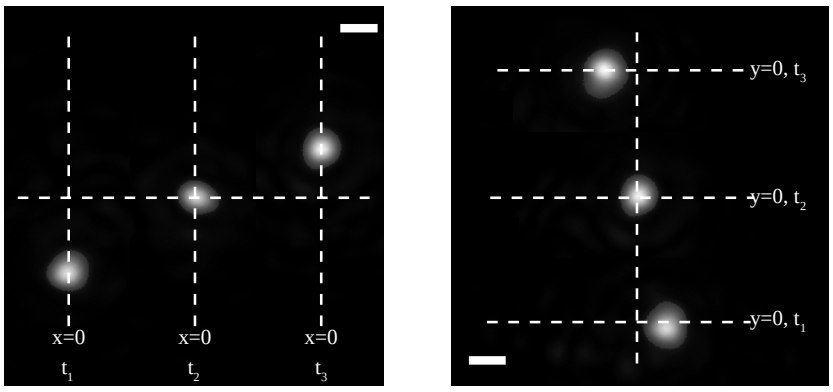

(a) (b)

Fig. 5. Scanning the focus using saved phase patterns (Media 1). Different calculated phase patterns where digitally saved and then reprojected onto the fiber. Utilizing this technique we can scan the focus. In the figure above, the focus is displaced vertically (a) and horizontally (b). The capability of scanning the focus can be crucial for the implementation of an all-optical scanning endoscope. Scale bar is equal to 5μm.

After having explored the robustness and the effectiveness of our method for focusing through a multimode fiber, we demonstrate the capability of scanning a focus point around the fiber field of view by employing optical methods only, i.e non-mechanical. For this, we rely on a major advantage of digital phase conjugation over conventional phase conjugation done with photorefractive materials, which is the freedom it offers on the digital handling of the acquired data. Once a phase pattern is calculated it can be saved in the computer for future use. In the proposed experimental setup, the calculated phase patterns for different positions of the focus point where digitally saved and thereafter projected sequentially onto the SLM. Snapshots of a video where the focus is scanned around the fiber surface are presented in Fig. 5. The whole video can be seen in the supplementary material, Media 1.

4. Conclusions

We have demonstrated a method for focusing and scanning light through a multimode optical fiber by using digital phase conjugation. The method is open loop. Only one image is required for the calculation of the correct wavefront, and therefore has great potential in dynamic applications where the fiber configuration can change. The generated focus at the fiber facet was diffraction limited by the fiber NA and had a contrast of 1800 compared to the background, an enhancement of 700 times compared to the case when no phase conjugation was deployed and was 38 times brighter than any bright speckle that was generated randomly by the modal scrambling. Moreover, by saving and projecting the calculated phase patterns sequentially, we were able to scan the focus point around the fiber field of view without compromising the quality of the focus. Based on the above, our technique is well suited for dynamic endoscopic imaging modalities that require high power to be transmitted through the fiber component. In a digital phase conjugation endoscope, the excitation can be generated for example, by a single mode fiber co-aligned with the multimode fiber such as in the geometry of a double clad fiber, or with multiple single mode fibers placed around the multimode fiber core. The actuator-free optical scanning of the focus allows us to achieve an endoscope size limited only by the fiber diameter.

Acknowledgments

We would like to thank Jean-Pierre Huignard for his insightful comments on digital phase conjugation and for discussions related to this work and Alexandre Goy for providing computer software. This project was conducted partially with the support of the Bertarelli Foundation under the grant “Optical Imaging of the Inner Ear for Cellular Diagnosis and Therapy: Cochlear Implants and Beyond”.