

# Focusing and scanning light through a multimode optical fiber using digital phase conjugation

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**Abstract:** We demonstrate for the first time to our knowledge a digital phase conjugation technique for generating a sharp focus point at the end of a multimode optical fiber. A sharp focus with a contrast of 1800 is experimentally obtained at the tip of a 105 $\mu$ m core multimode fiber. Scanning of the focal point is also demonstrated by digital means. Effects from illumination and fiber bending are addressed.

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**OCIS codes:** (090.1000) Aberration compensation; (090.1995) Digital holography; (070.5040) Phase conjugation; (110.7050) Turbid media; (060.2310) Fiber optics.

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## 1. Introduction

Deterministic transmission of an optical field through a random medium has been of uttermost importance for many years. The ability to focus light through a scattering medium increases the imaging depth via two-photon imaging [1]. The turbid nature of biological tissue imposes random characteristics on the propagation of light through it, which tends to smear out a tightly focused spot. Optical phase conjugation has been proposed and experimentally implemented as a technique for suppressing the turbidity [2–5]. Digital phase conjugation avoids holographic recording materials through the use of a combination of digital holography and a spatial light modulator [6–8]. On the other hand, wavefront engineering mechanisms based on iterative optimization schemes [9,10] or the calculation of the transmission matrix [11] have been investigated recently for achieving the same result. All these advances pave the way for efficient transmission of light through a random medium.

An alternative approach for overcoming the challenges that the scattering imposes on deep tissue imaging, is to use an optical fiber as a minimally invasive endoscopic tool [12–14]. State of the art miniature fiber endoscopes are comprised of a single mode fiber based light delivery and scanning mechanism that rely on moving the fiber tip by piezo-actuators. Instead, multimode fibers with their larger number of degrees of freedom allow higher peak power transmission through the endoscope and possibly offer all-optical scanning of the excitation spot by manipulating these degrees of freedom. Therefore the need for mechanical actuators, that increases the size of the endoscope, can be eliminated. However, efficient light propagation through a multimode optical fiber does not come without difficulties. As the optical field is coupled into the fiber, it excites different modes which propagate along the fiber, possibly exchanging energy between them through intermodal coupling. Upon reaching the output fiber surface they interfere, generating what is seemingly a random speckle pattern. In this context it is possible to regard multimode fibers as the waveguide equivalent of bulk random media, with the difference that in the fiber the number of modes that is excited is not the same for different illumination conditions, whereas in a free space turbid medium the number of modes is statistically the same under all excitations.

Optical phase conjugation with photorefractive crystals has been proposed and experimentally realized for image transmission through a multimode optical fiber [15–17], as well as for the correction of polarization and modal scrambling in multimode fibers [18]. Moreover, in the field of optical communications, optical phase conjugation generated by Stimulated Brillouin Scattering effect (SBS) has been utilized for beam cleanup in multimode optical fibers [19]. Although the mentioned techniques laid the foundations for the application of phase conjugation in overcoming the scattering properties of multimode optical fibers, they suffer from the inherent disadvantages linked to the use of photorefractive crystals i.e 1. wavelength specificity of the photorefractive crystals 2. slow response times and 3. the complexity of the system in the case of multiplexing different holograms, makes these implementations less exciting compared to the modern digital version of optical phase

conjugation. Recently, different groups have successfully applied wavefront optimization iterative methods in order to achieve focusing of light through a multimode optical fiber. Bianchi et al. [20,21] along with Čižmár et al. [22] have demonstrated focusing of light and used it for micromanipulation of objects using multimode fibers. Although very interesting, the performance of these iterative techniques is compromised by the fact that they are time consuming and therefore can't offer a real time implementation of the focusing. In a multimode fiber, the optimal wavefront has to be recalculated continuously because of disturbed intermodal coupling, temperature and strain caused by fiber motion. Although an iterative implementation with a fast (32 kHz) amplitude digital micromirror array instead of a phase SLM has demonstrated phase optimization in 34ms [23], the system is power inefficient because of the amplitude holograms and image transfer speed reaches the limits of current electronics (40 GHz).

Digital phase conjugation is an implementation of optical phase conjugation where instead of exploiting the nonlinear properties of a crystal to generate the conjugate optical field, the actual phase of the distorted wavefront is calculated by the means of digital holographic recording. The calculated phase is then projected onto a Spatial Light Modulator (SLM) and is used to assign this information to an unmodulated beam, which finally forms the phase conjugate optical field. When the conjugate beam is backwards propagated through the random medium the distortions are undone and a clear version of the original image is generated on the input plane.

Digital phase conjugation has been explored as a means for coherently combining an array of 3 fiber amplifiers [6] and also for light manipulation in a Large Mode Area (LMA) fiber that supports 4 modes [24]. In the present paper, we demonstrate a digital phase conjugation method for focusing light as well as scanning through a multimode optical fiber. The system holographically records on the sensor the optical field at the output of the fiber and the phase is digitally retrieved from the captured hologram. Finally, the optical phase conjugated field is generated at one end and propagates through the multimode fiber to come into focus at the other end. This is an open loop system meaning that a single image is needed for the calculation of the correct wavefront. The time response of the system can be very fast, limited only by the time for the extraction of the phase from the captured hologram and the assignment of the phase onto the SLM. In general, this is performed in less than 30ms with state-of-the-art SLMs. Different calculated phase patterns can be stored digitally in a look up table and thus can be reassigned at a later moment. This capability will be exploited in order to optically scan the focus point around the fiber surface as was done in [22]. Furthermore, the effect of different illumination, center vs. edge illumination, as well as the effect of fiber bending on the quality of the generated focus point will be addressed.

## 2. Methods and experimental setup

The experimental setup used for the implementation of digital phase conjugation through the multimode fiber is depicted in Fig. 1. The laser source is a diode pumped Nd:YVO<sub>4</sub> Q-switched laser (EKSPLA NL-201) operating at 1064nm with a pulse width of 5ns and a repetition rate of 1kHz. For all the experiments conducted and presented here, the laser was used in the quasi-CW regime by turning the Q-switching off, therefore the whole experiment was conducted with a CW source.

The multimode fiber that was chosen, is a step index multimode fiber with a core diameter of 105 $\mu$ m and NA = 0.22. That, corresponds to a V-number of 68 and the number of supported modes, based on the formula  $N = 4/\pi^2 V^2$ , gives an estimate of 1870 propagating modes.

The laser output was directed towards the beam expander formed by the lenses L1 and L2 that result in a three fold magnification of the beam size, which is then split into two arms, one to be delivered to the fiber and the other to be used as the reference for the holographic recording. The beam is focused through a 40x microscope objective (NA = 0.65, OBJ1) onto

the step index multimode fiber facet (1m length, 105 $\mu$ m diameter core, NA = 0.22, Thorlabs AFS105/125Y step index multimode fiber). The generated focus is then coupled into the propagation modes of the fiber and generates a random speckle pattern at the output facet. The speckle pattern is imaged on the CMOS detector (Photonfocus MV1-D1312(IE)-G2, CMOS camera) through a 40x objective (NA = 0.65, OBJ2) and a tube lens of 20cm focal length, L3. The reference beam initially passes through the spatial filter comprised of a microscope objective (10x, NA = 0.25, OBJ3) a pinhole of 25 $\mu$ m diameter and a collimating lens, with  $f = 10$ cm (L4). The Gaussian expanded reference beam is directed towards the imaging plane by reflecting on the beamsplitter BS2 (R8:T92 pellicle beam splitter) thus generating an off-axis hologram. The recorded hologram is then treated numerically and the phase of the optical field on the output facet of the fiber is retrieved. The power ratio between the image and the reference beam can be controlled by rotating the half-wave plate placed before the polarizing beam splitter BS1.

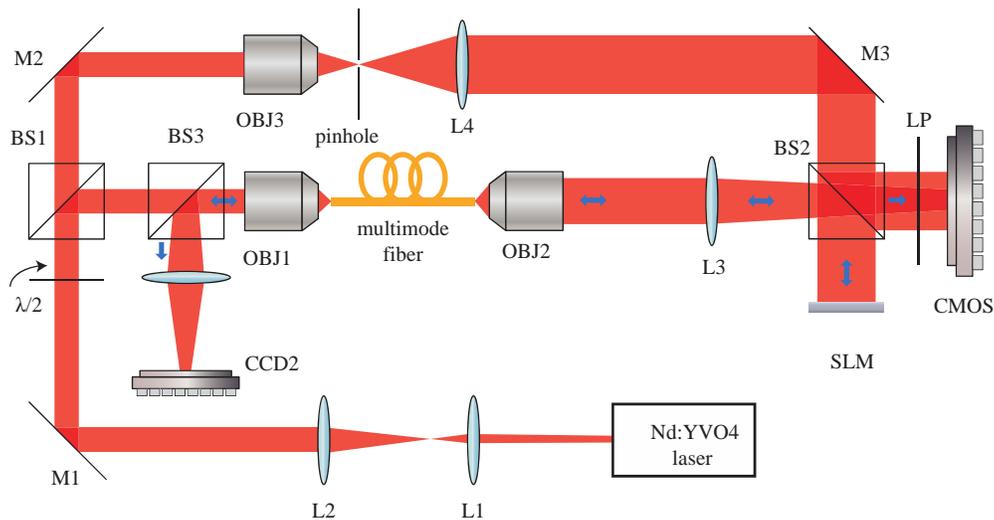


Fig. 1. Experimental Setup. The beam is expanded by the telescope formed by lenses L1-L2 and is split in two arms with the polarizing beamsplitter BS1. The spatial filter OBJ3, pinhole and L4 expand and clean up the reference beam. The other arm is focused on the fiber tip with the objective OBJ1. The output of the fiber is imaged on the CMOS sensor through the 4f imaging system (OBJ2 and L3). The reference is combined with the image by reflecting on the non-polarizing beamsplitter BS2 generating a hologram. The phase conjugate beam is generated by the calculated phase on the SLM and the reference beam and is redirected towards the fiber by reflecting again on BS2. The quality of the generated focus can be examined by the imaging system in reflection, OBJ1 L5 on CCD2 through the non-polarizing beamsplitter BS3.

The recorded hologram is digitized and the phase of the incident wavefront is calculated in the computer. The calculated phase is then projected onto the phase-only SLM (Pluto-NIR II, Holoeye) and is picked up by the same beam that was used as the reference. Finally, the conjugate optical field that is generated in this way is reflected back into the imaging line by the beamsplitter BS2 and projected onto the fiber facet through the 4f imaging system (tube lens L3 and microscope objective OBJ2). The conjugate field propagates backwards through the multimode optical fiber and is focused at the input fiber tip. The alignment process is very critical on the final efficiency of the digital phase conjugation system. The sensor and the SLM need to be aligned pixel by pixel so that the correct phase conjugate beam is formed. This prerequisite is taken care of before the final implementation of the experiment.

The image on the input plane and therefore the quality of the focus is observed through the imaging system that is composed by the excitation objective, OBJ1 and the 20cm focal length tube lens L4, on the sensor CCD2 (Baumer TXF-14 CCD camera).

### 3. Results and discussion

The laser beam is focused with the use of a 40x microscope objective (OBJ1) onto the fiber input facet. The excitation spot is measured on the CCD2, as the fiber tip reflects back part of the energy. Exploiting this, the beam waist,  $w_0$ , of the excitation spot is measured and is equal to  $2.25\mu\text{m}$ . As the entrance pupil of the excitation objective is not completely illuminated, the waist of the excitation spot is larger than  $\lambda$  over  $2\text{ NA}$ .

The speckle pattern generated at the output of the fiber is presented on Fig. 2(a). As we can observe, the speckles are both randomly and uniformly distributed over the whole fiber facet indicating that a large number of the supported modes are excited and interfere at the output. The phase of the optical field, calculated by the captured hologram is presented in Fig. 2(b). The phase is presented without the constant linear phase that is the contribution of the off-axis configuration of the holographic setup. Assigning the phase to the unmodulated beam with the use of the phase-only reflection SLM, and letting the phase conjugated field propagate back through the multimode fiber, we observe a very sharp focus spot being generated at the input facet of the fiber, Fig. 2(c), exactly at the same position where the excitation was. The contrast of the focus, which is defined as the peak value over the mean of the background, was evaluated to be  $\sim 1800$ .

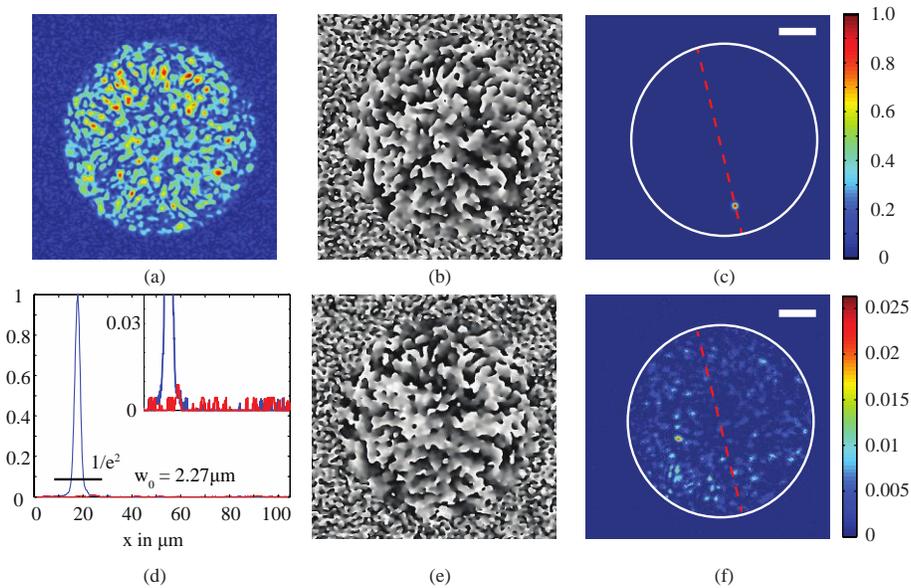


Fig. 2. Focusing through a multimode fiber using digital phase conjugation. (a) Reconstructed speckle pattern at the output of the fiber as a result of a focus propagating along the multimode fiber. (b) Calculated phase. The constant linear phase contribution from the off-axis holographic setup has been removed. (c) Phase conjugated focus point at the input of the fiber. The focus is created at exactly the same position as the excitation and the contrast is calculated  $\sim 1800$ . (e), (f) Random phase pattern and the corresponding image at the output of the fiber. Clearly no focusing effect can be observed. The optical field propagates and again gets scrambled. (d) Profiles of the fiber input after phase conjugation along the red dashed line drawn in (c) and (f). In blue the profile after phase conjugation and in red the profile without. The beam waist of the phase-conjugated focus is  $2.27\mu\text{m}$ . Without the phase conjugation the field appears as random speckles and the overall enhancement resulting from the phase conjugation is  $\sim 700$  times. (d) Inset. Detail of the plot where the limits of the y-axis are set from 0 to 0.04. The white circle in (c) and (f) defines the multimode fiber core. Scale bar in (c) and (f) is  $20\mu\text{m}$ .

On the contrary, if the beam is modulated with a random phase pattern, as depicted in Fig. 2(e) no focusing is observed. The field gets scrambled while propagating, generating a new random speckle pattern at the input facet, Fig. 2(f). The enhancement achieved using digital phase conjugation is  $\sim 700$  times, calculated as the ratio of the peak value of the focus over the mean of the field generated by a random phase pattern. The images captured in Fig. 2(c) and 2(f) are with the same power transmitted through the fiber and both images were normalized to the peak value of the focus point. Moreover, it can be observed that the focus point generated by digital phase conjugation is 38 times brighter than any random speckle caused by the modal scrambling. This result demonstrates that digital phase conjugation is an efficient way for producing an intense focus through multimode optical fibers.

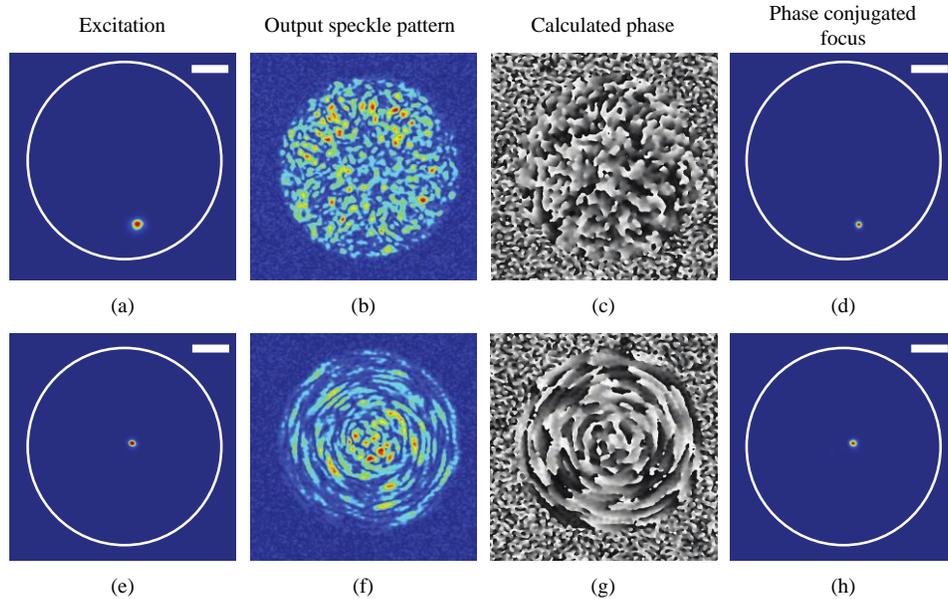


Fig. 3. Center vs. edge illumination. Excitation, output speckle pattern, calculated phase and phase conjugated focus for excitation close to the edge of the fiber (a)-(d), and for excitation at the center (e)-(h). When the fiber is illuminated in the center mainly the radially symmetric modes are excited. In both cases the phase conjugation is able to generate a sharp focus point at the input of the fiber. Statistical examination of the results though, reveals that the average contrast (peak value over mean of the background) for the case of center illumination is  $\sim 920$  whereas for the case of edge illumination it is  $\sim 1800$ . Edge illumination excites more modes in the fiber, which in turn offer a higher number of degrees of freedom for the compensation of the distortion. Scale bar in (a), (d), (e) and (h) is  $20\mu\text{m}$ , the white circle defines the fiber core outline and the images are normalized to their maximum value.

The earlier work on focusing of light through a random medium (inhomogeneous free space or a multimode fiber) by iterative approaches showed that the number of degrees of freedom one can manipulate affects the performance of the focusing system [9]. In the case of propagation of light through a multimode fiber, the available degrees of freedom correspond to the number of propagation modes involved. By investigating two different excitation geometries, we prove that this argument also holds for digital phase conjugation through a multimode fiber. The first row of Fig. 3 corresponds to an excitation placed near the edge of the fiber, whereas the second row corresponds to an excitation field well aligned to the center of the fiber core. Illuminating at the center of the fiber core causes only the radially symmetric modes to be excited. The generated speckle pattern, Fig. 3(f), clearly suggests that a smaller number of modes are excited compared to Fig. 3(b). The phase conjugated foci that are produced in both cases are presented in Fig. 3(d) and 3(h). In both cases, digital phase

conjugation is capable of reproducing the sharp focus at the input facet of the fiber. A better investigation of the images, reveals that in the case of the central illumination the measured contrast is  $\sim 920$ , almost half the measured contrast for the case of the edge illumination which was calculated  $\sim 1800$ . This difference can be explained by the fact that the edge illumination excites more propagation modes inside the multimode fiber, as has been already indicated by the comparison of the generated speckle patterns (see Fig. 3(b), 3(f)). The larger number of modes means that there are more degrees of freedom available for the compensation of the wavefront distortion; therefore a higher quality focus can be produced.

In order to assess the effects of the bending of the fiber to the quality of the phase conjugated focusing, the experiment was repeated with a fiber excited at the center but extreme bending was applied on the fiber at a certain position. The radius of the bending applied was smaller than 1cm so that high losses and birefringence was induced on the modal propagation, however, the losses are not the same for the different propagation modes. As can be observed in Fig. 4(c) the digital phase conjugation setup is able to reproduce the focus at the input facet. However, in this case the focused spot deviates from the ideal circular shape, as information (modes) is lost due to the fiber bending. Numerical processing of the image shows that the contrast of the focus has decreased to only 400. Since phase conjugation cannot compensate for losses induced during propagation [25], the deterioration of the phase conjugate spot quality is expected for the bent fiber.

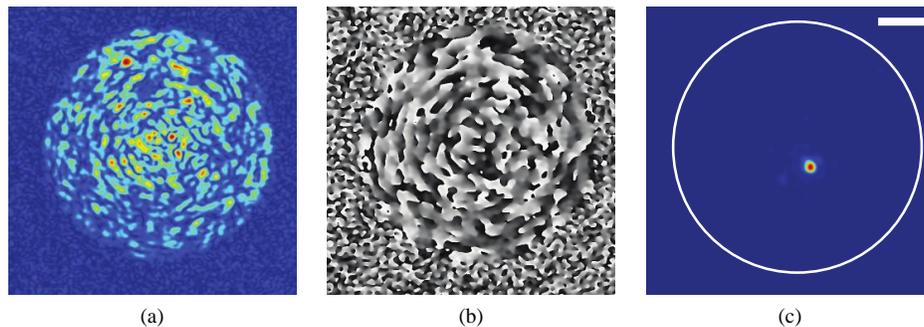


Fig. 4. Focusing using digital phase conjugation through a tightly bent multimode fiber. The bending induces losses on the mode propagation. The focus can still be retrieved however, phase conjugation cannot compensate for the losses, therefore the quality of the focus has deteriorated and the measured contrast is only  $\sim 400$ . This case is analogous to phase conjugation through an absorptive scattering medium. Scale bar in (c) is  $20\mu\text{m}$ , white circle outlines the fiber core and the image is normalized to its maximum value.

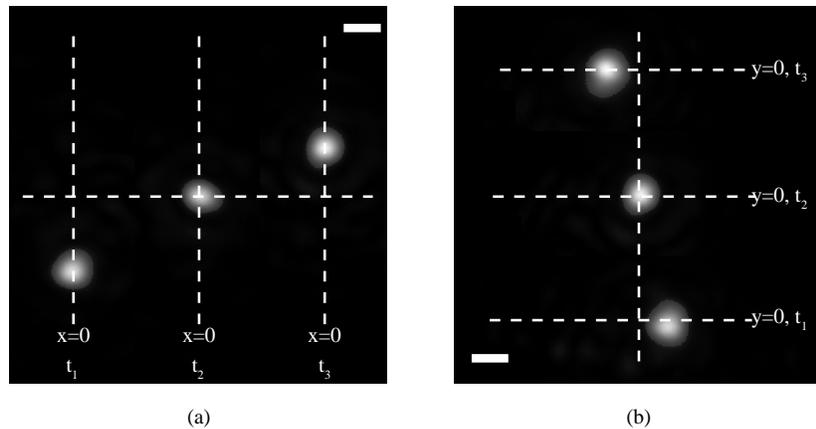


Fig. 5. Scanning the focus using saved phase patterns (Media 1). Different calculated phase patterns were digitally saved and then reprojected onto the fiber. Utilizing this technique we can scan the focus. In the figure above, the focus is displaced vertically (a) and horizontally (b). The capability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

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 were 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”.