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Laser-Doppler-Messungen durch eine Multimode-Faser mittels digitaler optischer Phasenkonjugation

Laser Doppler measurements through a multimode fiber using digital optical phase conjugation

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Laser Doppler Anemometrie, Multimode-Faser, endoskopische Messung, Phasenkonjugation
laser Doppler velocimetry, multimode fiber, endoscopic measurement, phase conjugation

Summary

The utilization of optical fibers is attractive for laser-based flow measurement methods. The main advantage is that the light source can be physically separated from a compact, purely-passive optical measurement head which enables a comfortable handling and high flexibility with respect to its application. Due to their small size, fibers can potentially be employed to realize endoscopic measurement heads. Whereas singlemode optical fibers preserve the high beam quality of lasers, multimode fibers require less effort for incoupling and are able to transmit considerably higher light powers. However, light coupled into a multimode fiber is subject to mode scrambling within the fiber, such that any defined light pattern at the fiber input turns into an apparently random speckle pattern at the output. Due to this speckle noise, attempts to utilize multimode fibers for beam delivery in flow measurement were not pursued further.

In this contribution we present the application of digital optical phase conjugation (DOPC) to overcome this problem and to transmit an interference fringe system through a multimode fiber. The light field at the fiber input is shaped by a complex phase mask displayed on mega-pixel spatial light modulator such that a fringe system is formed at the fiber output. The fringe system is used to perform velocity measurements based on laser Doppler velocimetry. We show that the fringe system is localized at a certain distance with respect to the fiber facet and that the axial position of the fringe system can be changed by displaying different phase masks, what can be used to scan flow profiles. Here we present the principle of DOPC and the fringe pattern generation and demonstrate velocity measurements at air flow emitted from a nozzle as an example.

Since in principle no further imaging optics is needed behind the fiber to generate the fringe system, the idea has the potential to realize endoscopic setups for the applications in surroundings with very restricted access, e.g. turbo machines or living organisms.

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Introduction

The utilization of optical fibers is attractive for laser-based flow measurement methods. The main advantage is that the light source can be physically separated from a compact, purely-passive optical measurement head which enables a comfortable handling and high flexibility with respect to its application. Moreover, they exhibit an immunity against electromagnetic disturbances, as they occur e.g. in the proximity of large power units. Optical fibers can be divided into two classes, single- and multimode fibers. Singlemode optical fibers preserve the excellent beam quality of lasers (Gaussian beam), but require high effort and mechanical stability for incoupling of the light. Multimode fibers, on the other hand, require less effort for incoupling and are able to transmit considerably higher light powers. Because of these advantages, multimode fibers have been early recognized and investigated for beam delivery also for flow measurement techniques [1], but due to the occurring speckle pattern, an effect of mode interference within the fibers, these attempts were not pursued. In the early 2000s, an approach of a laser Doppler velocimeter (LDV) with light delivered from a multimode fiber has been presented, where the coherence properties of the emitted light have been purposefully exploited to reduce speckle noise significantly on the one hand, and to generate a short measurement volume with high spatial resolution on the other hand. However, an imaging optics behind the fiber is required here as well, making it difficult for endoscopic measurements with restricted access.

In this contribution we aim to overcome this problem by the utilization of Digital Optical Phase Conjugation (DOPC). Laser Doppler velocimetry (LDV) is based on a localized fringe system forming by interference in the volume of intersection of two crossing coherent laser beams. The idea is to transmit a fringe system directly through a multimode fiber based on DOPC, as shown in Fig. 1.

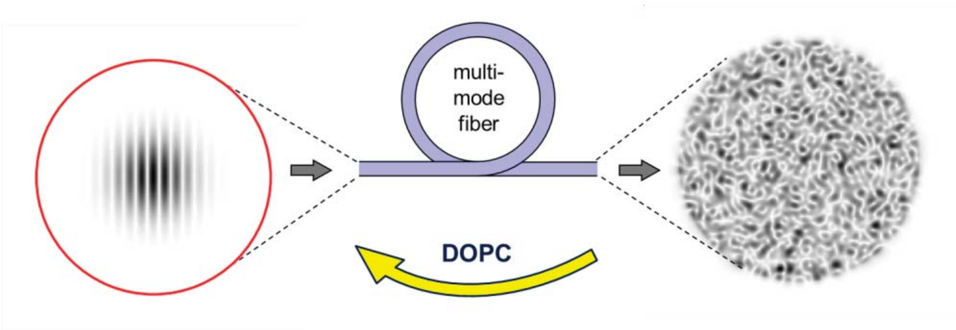

Fig. 1: Principle of transmission of a fringe system through a multimode optical fiber by means of Digital Optical Phase Conjugation

Experimental Setup: Digital Optical Phase Conjugation

A solid-state laser with 532 nm wavelength and up to 5 W optical power is used as the light source. The emitted beam is split into two paths, an object path propagating through the multimode fiber and a reference path. The first path is used to generate the guide star, here a fringe system is incoupled into the multimode fiber at distal side. The resulting speckle pattern at the proximal side is recorded using off-axis-holography with the second beam. In the playpack operation, the plane reference wave is modulated with a phase-only spatial light modulator (Holoeye Pluto, 1920 x 1080 pixels, 8 µm pixel pitch) to playback the guide star in opposite direction with conjugated phase. This leads to a fringe system at the distal side transmitted through the fiber. A scheme of the setup is shown in Fig 2.

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The fringe system on distal side is generated by a Mach-Zehnder-Interferometer. The proximal fiber tip is imaged to the SLM, which is imaged to CMOS1 for acquisition of the hologram. CMOS2 is imaged to the distal fiber tip to observe and optimize the playback. The quality of the playback is further enhanced by modulating both polarization states with the SLM (not shown in Fig. 2.)
Fig. 3 shows the playback of a fringe system at the fiber tip using DOPC. For the measurement of a macroscopic flow the measurement volume was imaged with the microscope objective and a second lens to increase the working distance.

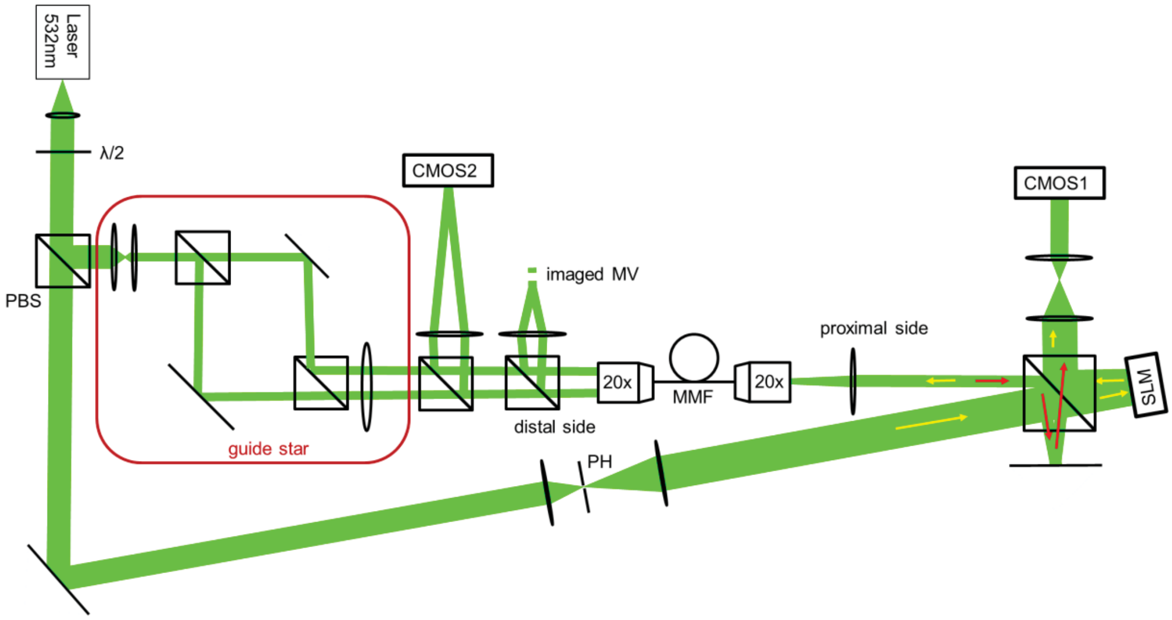

Fig. 2: Scheme of experimental setup to transmit a localized fringe system through a multimode fiber. Red and yellow arrows denote the guide star and the reference beam, respectively. The guide star is generated by the components in the red box (Mach-Zehnder interferometer). It generates the fringe system of an LDV by making the two partial beams intersect in front of the fiber facet. The guide star is blocked during playback. PBS: Polarizing Beam Splitter. PH: Pinhole.

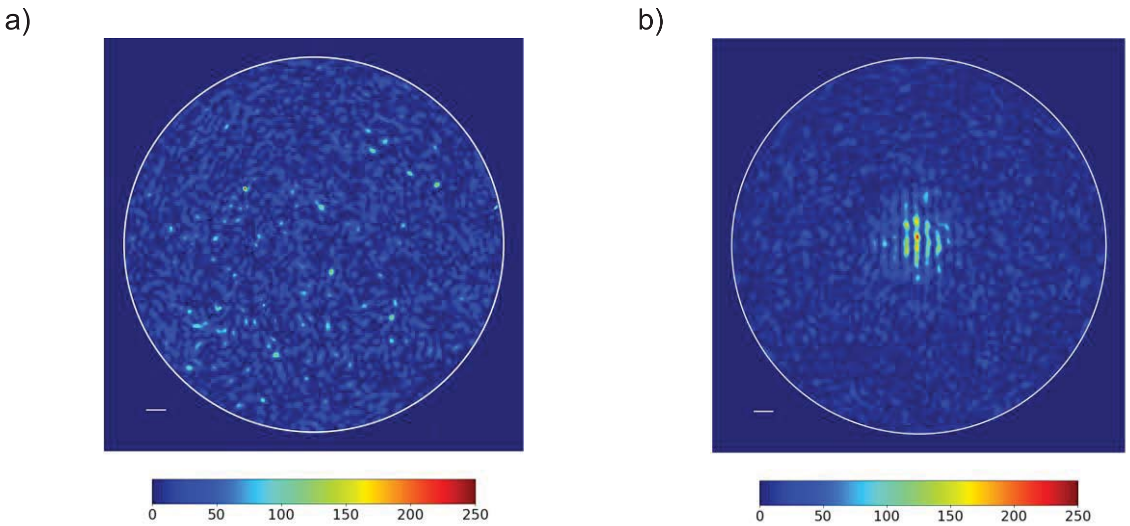

Fig. 3: Measured intensity profile of a step-index multimode fiber (diameter 100 µm, numerical aperture NA=0.22) output a) without and b) with the application of a phase-conjugated light field. Scale bar is 10 µm.

Simulation

The light transport through fibers can be described using modes and a transfer-matrix describing the mode mixing mainly caused by impurities, stress and bending. A simulation (concerning only one polarization state) indicate that for fibers with a diameter larger than 30 µm a localized fringe system in the VIS-spectrum can be transmitted using DOPC. The working distance, fringe spacing and measurement volume is mainly restricted by geometrical optics described by the numerical aperture and core diameter of the fiber. Fig. 4 shows as an example the simulated playback of a localized fringe system using DOPC.

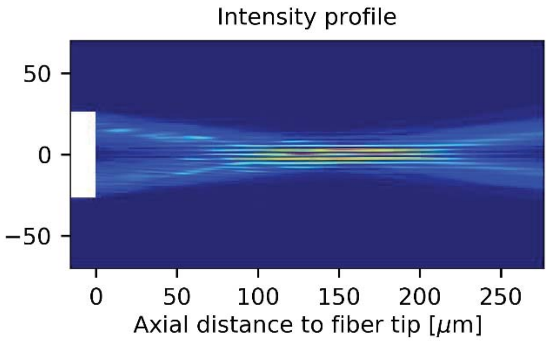

Fig. 4: A simulation of the light propagation after DOPC reveals how a localized fringe system is formed behind the fiber without any further optical elements, representing the measurement volume of an LDV. Shown is the intensity distribution in a cross-sectional plane through the optical axis. The white bar represents the core of a multimode fiber of 50 µm diameter.

Experimental Results: Flow Measurements

The interference fringe system appearing behind the fiber facet during playback was imaged by a Keplerian telescope with a magnification of 2.5 into free space. The imaged measurement volume had a diameter of 30 µm, a length of 200 µm and a fringe spacing of 4.9 µm.

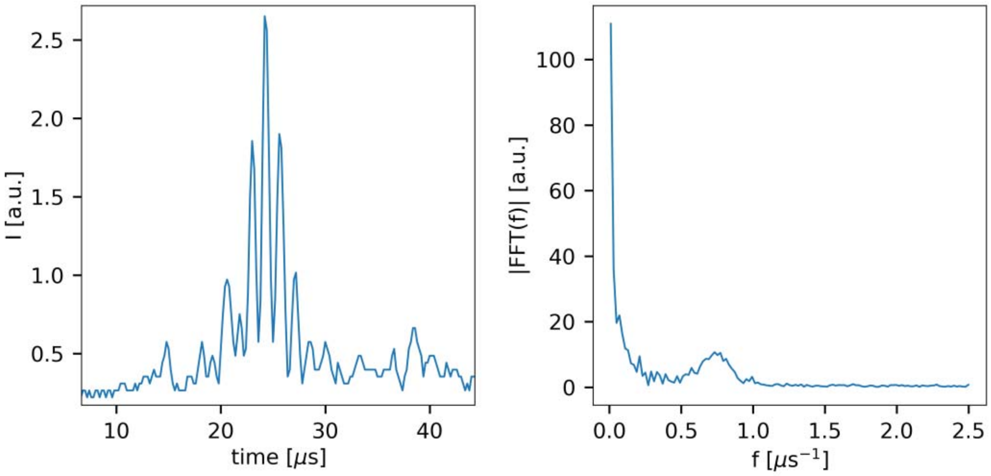

Fig. 5: Doppler signal obtained from a water droplet, shown a) in the time domain, and b) in the frequency domain. Despite a remaining speckle background which is obvious in the time signal (compare Fig. 3b), a clear Doppler peak can be observed in the spectrum for evaluation of the velocity.

Flow measurements were performed at nozzle flow seeded with polydisperse water particles (TSI Single-Jet Atomizer Model 9302, mean droplet size 4...5 µm) 8 mm behind the nozzle exit. The light scattered from the particles was detected by a photodetector and evaluated on a PC. Fig. 5 shows the burst signal of a single water droplet in the time and frequency domain. The flow velocity profile was obtained by mechanically traversing the nozzle in axial direction, see Fig. 6. This provides proof that laser Doppler measurements can successfully by conducted with light delivered by a multimode-fiber and the application of DOPC.

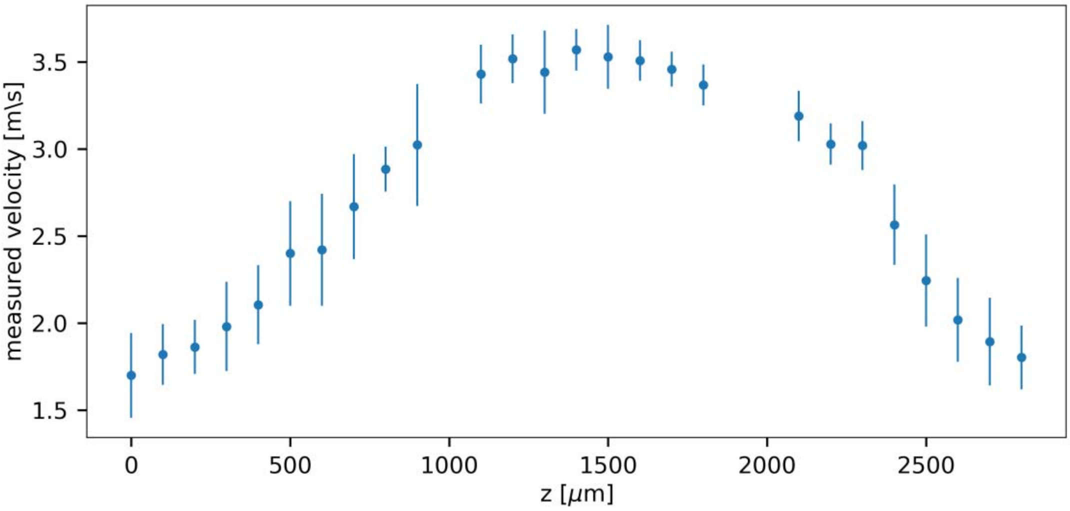

Fig. 6: Flow velocity profile measured behind the nozzle.

The axial size of the measurement volume behind the fiber is shown Fig. 7, which was calculated using the imaging equations. During calibration, different phase masks were recorded for different axial positions of the interference fringe system with respect to the fiber facet. When displaying these phase masks during playback, the LDV measurement volume can be reproduced at different axial positions. In principle, this can be used for scanning a velocity profile with mechanically moved parts.

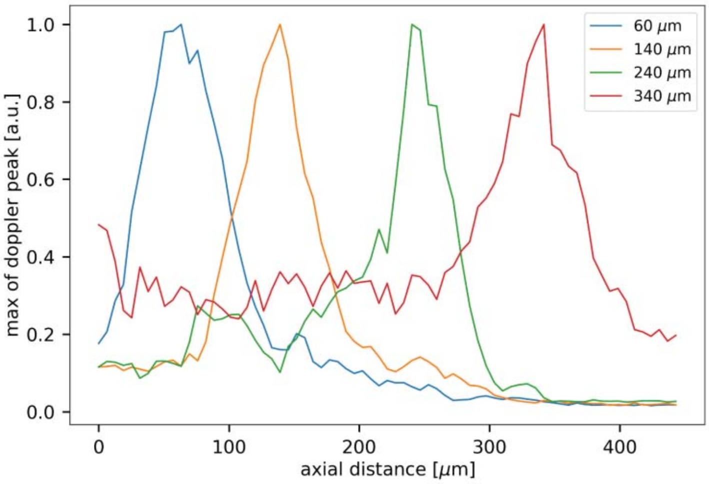

Fig. 7: Outlook: Axial Scanning can be performed by displaying different phase masks on the SLM, here marked with different colors. The plot shows the amplitude of the Doppler peak along the optical axis, representing the axial extent of the measurement volume.

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Conclusion and Outlook

The employment of multimode optical fibers for light delivery in laser Doppler velocimeters can offer advantages for practical handling and can even open perspectives towards new applications. Here we aim to demonstrate an endoscopic LDV that needs no imaging optics at the fiber end. The idea is based on digital optical phase conjugation (DOPC) that allows for transmitting a structured light pattern through the multimode fiber. In a calibration step, the interference fringe system is guided through the fiber and the emitted speckle field is measured holographically. In the measurement step, the measured phase distribution is conjugated, displayed on a spatial light modulator and guided back through the fiber. We showed that a localized fringe system can be reproduced in free space at a certain distance with respect to the fiber end without any further imaging optics. This fringe system can be used to perform laser Doppler measurements based on conventional LDV. A measurement of an air flow emitted from a nozzle was demonstrated. By displaying different phase masks on the modulator, the position of the measurement volume can be changed. This can be used in the future to achieve a scanning measurement of the velocity profile of the flow in the proximity of the fiber tip without any mechanical movement.

The presented method exhibits a potential for flow measurements in environments with very limited mechanical access, e.g. in micro channel, in turbo machines or for in vivo blood flow measurements of model organisms.

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