Video Article

Transmission of Multiple Signals through an Optical Fiber Using Wavefront Shaping

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Abstract

The transmission of multiple independent optical signals through a multimode fiber is accomplished using wavefront shaping in order to compensate for the light distortion during the propagation within the fiber. Our methodology is based on digital optical phase conjugation employing only a single spatial light modulator, where the optical wavefront is individually modulated at different regions of the modulator, one region per light signal. Digital optical phase conjugation approaches are considered to be faster than other wavefront shaping approaches, where (for example) a complete determination of the wave propagation behavior of the fiber is performed. In contrast, the presented approach is time-efficient since it only requires one calibration per light signal. The proposed method is potentially appropriate for spatial division multiplexing in communications engineering. Further application fields are endoscopic light delivery in biophotonics, especially in optogenetics, where single cells in biological tissue have to be selectively illuminated with high spatial and temporal resolution.

Video Link

The video component of this article can be found at https://www.jove.com/video/55407/

Introduction

The transmission of multiple light signals through a multimode fiber (MMF) is evident in communications engineering[1] and biophotonics[2]. In communications engineering, space-division multiplexing (SDM) is believed to be a viable solution in order to enhance the transmission capacity of optical fibers for future data transfer applications benefiting from a higher utilization of the limited space, compared to multiple single-mode fibers[3]. In biophotonics, biological samples are manipulated by light transmitting through an MMF endoscope[4]. For example, the independent optical control of individual neurons using MMF endoscopes is of interest for optogenetics in order to study neuronal networks in the brain[5]. However, the light projected onto the MMF input facet is subject to distortion due to mode mixing and dispersion during propagation to the output facet of the MMF. As a result, the light propagation is altered, which makes signal transmission challenging.

Wavefront shaping methods[6,7] are applied in scattering media using spatial light modulators (SLM) and enable the compensation for the distortion due to scattering during light propagation[8]. There are iterative approaches that optimize the output using an optical feedback[9]. These approaches are rather time consuming because of the necessity for numerous iterations and the high degree of freedom, corresponding to a large number of modulator elements. Another approach is to completely determine the distortion within the MMF described by its transmission matrix[10]. If the number of modes to be transmitted is large, this will be time consuming as well. In contrast, digital optical phase conjugation (DOPC) is considered to be fast and advantageous here, since only few focal spots have to be generated at the output facet of the MMF. Phase conjugation approaches have also been demonstrated for focusing or imaging through biological tissue[12,13,14].

So far, DOPC was employed for a single time signal only[15,16], and was applied for the transmission of light through an MMF[17]. A DOPC approach for multiple independent signals has not been accomplished. We have developed an enhanced DOPC method providing the independent transmission of multiple light signals using individual wavefront shaping for each signal employing a single phase-only SLM[18]. To this aim, the SLM is segmented into regions, one for each signal to be transmitted. The proposed experimental setup is depicted in **Figure 1**, where a calibration is performed in a) before the actual transmission happens in b).

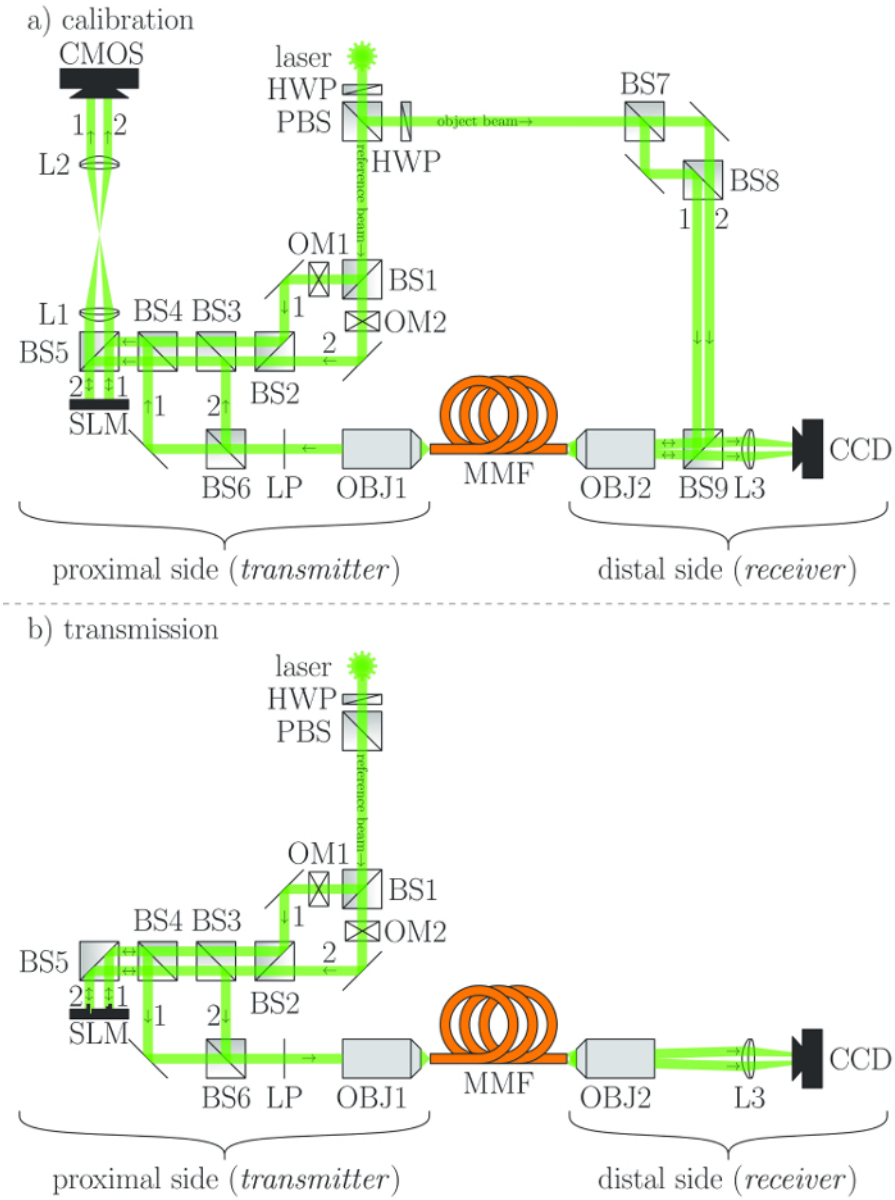

Figure 1: Experimental setup. BS = beam splitter, CCD = charge-coupled device, OM = optical modulator, CMOS = complementary metal-oxide semiconductor, HWP = half wave plate, L = lens, LP = linear polarizer, MMF = multimode fiber, OBJ = microscope objective, PBS = polarizing beam splitter, SLM = spatial light modulator (phase only) — only relevant beams for (**a**) the calibration and (**b**) the transmission are depicted Please click here to view a larger version of this figure.

Protocol

1. Assembling the Experimental Setup

1. **Preparing the proximal side**
    1. Place and fix the laser providing a collimated light beam – or use a fiber-coupled laser with collimation optics at the exit facet of the fiber.
    2. Put the polarizing beam splitter (PBS) to split the laser beam into reference and object beam. Turn the orientation of the half wave plates (HWP) by rotating the HWP in its rotation mount until the power of reference beam and object beam (at the distal side) is roughly the same. Check this by putting a screen into both reference and object beam. Choose the orientation of the PBS so that the polarization of the reference beam fits the polarization-sensitive spatial light modulator (SLM).
    3. Put a beam splitter (BS) into the reference beam to split the reference beam into two beams. Place the optical modulators (OM) such that these two beams coming from BS1 can pass OM1 and OM2, respectively.
    4. Combine the two beams passing OM1 and OM2 at BS2 employing two mirrors. Adjust the beam splitters and mirrors so that both beams are spatially separated.

5. Carefully align BS5 to ensure that the direction of incidence of both beams is perpendicular to the pixel plane of the SLM, ignoring BS3 and BS4 at first. At first, nothing is displayed on the SLM, *i.e.*, it acts like a mirror until the end of the calibration (throughout step 2).
6. Adjust the position and the distance between the two lenses (L) constituting a Keplerian telescope in order to get a sharp image of the SLM plane on the complementary metal-oxide semiconductor (CMOS) camera. Watch the correct orientation of L1 and L2 (flat sides are facing each other) to minimize aberrations.

2. **Preparing the distal side**
   1. Use BS7 to split the object beam into two beams and combine them at BS8 employing two mirrors. Again, adjust the beam splitters and mirrors so that both beams are spatially separated.
   2. Deflect both beams using BS9 to aim them to the microscope objective (OBJ). Focus OBJ2 on the distal end of the multimode fiber (MMF). Check the focus by observing the back reflection from the MMF employing L3 and a charge-coupled device (CCD) camera.

3. **Connecting proximal and distal side**
   1. Collimate the light from the object beam exiting the MMF employing OBJ1.
   2. Split the object beam using BS6, ignore the linear polarizer (LP) at first. Combine both object beams with both reference beams at BS3 and BS4 employing a mirror. Adjust the beam splitters and mirrors so that each pair of reference and object beam overlap at the SLM, intersecting with a small angle (less than 1°).
   3. Ensure that the power of the reference and the object beam are approximately equal by turning the orientation of the HWP, according to step 1.1.2.
   4. Check the interference pattern (off-axis hologram) at the CMOS camera and adjust the intersection angle accordingly. Increase the angle, until the interference fringe spacing roughly equals the size of two pixels on the CMOS camera.
   5. Adjust the orientation of the LP to match the polarization of object and reference beam in order to get a maximum contrast of the interference pattern in the CMOS camera image, so that the camera image shows distinct fringes.

2. Calibrating the System

1. **Calibrating the pixel relation between SLM and CMOS**
   1. Illuminate the whole SLM using only one of the reference beams and block the other reference and objects beams.
   2. Capture an image of the SLM with the CMOS camera.
   3. Get the coordinates of the upper left corner of the SLM in the CMOS camera image, *e.g.* using graphics software and the mouse cursor at the PC. Use these pixel coordinates as the point of origin regarding the SLM.
   4. Remove all beam blocks.

2. **Calibrating the signal paths**
   1. Block both reference beam 2 and object beam 2.
   2. Capture an image of the hologram with the CMOS camera. Evaluate the phase in the recorded hologram using angular spectrum method[19]. Calculate the inverted phase in the corresponding region of beam 1.
   3. Remove the former beam blocks and now block both reference beam 1 and object beam 1.
   4. Capture an image of the hologram with the CMOS camera. Measure the phase in the recorded hologram using angular spectrum method again. Calculate the inverted phase at the corresponding region of beam 2.
   5. Remove all beam blocks.

3. Transmitting the Signals

1. Block the object beam.
2. Stitch the calculated inverted phase images at the corresponding regions of beam 1 and 2 together and display the entire image on the SLM, typically using the computer graphics port.
3. Start the modulation of the input signals 1 and 2 by activating OM1 and OM2.
4. Observe the output signals 1 and 2 on the CCD camera.

Representative Results

Typical output signals at the distal side of the 2 m long fiber are depicted in **Figure 2**. Note that the desired focal spot (peak) is accompanied by an undesired speckle pattern (background), which is due to imperfection of the DOPC as a matter of principle. The corresponding peak-to-background ratio (PBR) amounts to 53 (solely signal 1 is 'on'), 36 (solely signal 2 is 'on') and 20 (both signals 1 and 2 are 'on') here, respectively. The PBR can be increased when a fiber that supports a larger number of modes (currently: 1710) is used.

Due to the finite PBR, a crosstalk results between the output signals, which is visualized in **Figure 3**. The crosstalk between to periodic signals with the frequencies f1 and f2 amounts to -24 dB (from signal 2 to signal 1) and -29 dB (from signal 1 to signal 2).

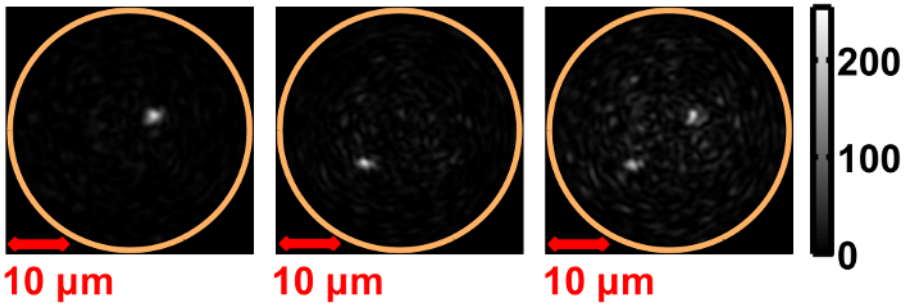

Figure 2: Image of distal fiber end, transmission of output signal 1 (left), signal 2 (center) and both signal 1 and signal 2 (right). Intensity [a. u.] Please click here to view a larger version of this figure.

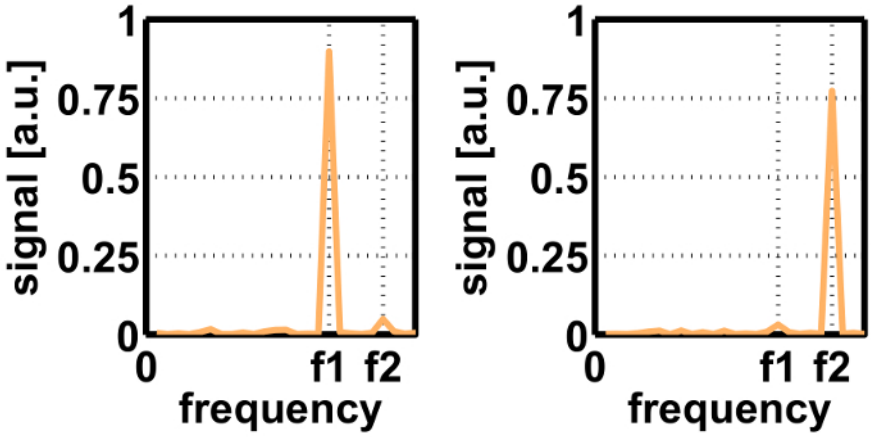

Figure 3: Temporal frequency spectrum of the transmitted output signal 1 (left) and 2 (right). Amplitude [a. u.] Please click here to view a larger version of this figure.

Discussion

The assembling of the experimental setup (step 1 in the protocol) requires a thorough alignment of the optical components with respect to each other. The most important aspect is the rectangular incidence of the reference beams onto the SLM in order to ensure a high PBR.

In order to enhance the setup to more than two transmitted signals, additional beam splitters could be used. As an alternative, a fiber-based implementation would be more compact and robust allowing the system to be portable for *in situ* investigations in biophotonics. If a single-side access is possible only, model-based calibration solutions[20] need to be accomplished as a future step. The more signals are transmitted, the more modes will be required so more pixels on both the SLM and the CMOS camera will have to be involved for achieving a PBR. Moreover, the number of pixels should be larger than or equal to the number of modes. In addition, the pixel size of the SLM should be twice the size of the smallest speckle diameter at the proximal side. It is further recommended that the SLM has a bit depth of at least four bit. The pixel number of the camera denoted with CMOS should exceed the number of the SLM pixels. However, instead of the CMOS camera any other detector type may be employed, *e.g.* CCD. The same holds for the camera denoted with CCD.

One limitation of the proposed method is that the light source requires a large coherence length (low spectral bandwidth) to assure interference in the hologram needed for the phase measurement. In addition, the system must be stable, *i.e.* no changes of the fiber or the optical setup between the calibration and the transmission are tolerable that are faster than the duration of the calibration, which is currently below 1 s. For long fibers and high signal frequencies, the group velocity dispersion of the different fiber modes has to be taken into account and may deteriorate the signal. To compensate for that, gradient-index fibers or the correction of spatiotemporal distortions[21] may be used.

In contrast to previous phase conjugation approaches, our proposed SDM method can be used in applications, where independent light signals have to be transmitted. Phase conjugation methods are advantageous regarding time performance, compared to iterative approaches or complete matrix determination.

One further potential application field may be endoscopic light delivery, for instance at optical traps or in optogenetics. For optogenetics, our method is advantageous regarding the selective illumination of single neurons in order to analyze the behavior of the brain and better understand neurodegenerative diseases.

Disclosures

The authors have nothing to disclose.

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