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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.
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TITLE:
Transmission of multiple signals through an optical fiber using wavefront shaping

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KEYWORDS:
digital optical phase conjugation, spatial light modulator, digital holography, communications engineering, biophotonics, optogenetics, endoscopy

SHORT ABSTRACT:
We demonstrate the transmission of multiple independent signals through a multimode fiber using wavefront shaping employing a single spatial light modulator. By modulating the wavefront for each signal individually, spatially separated foci are transmitted. Potential applications are multiplexed data transfer in communications engineering and endoscopic light delivery in biophotonics.

LONG 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.

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[12-14].

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).

[Place Figure 1 here]

PROTOCOL:

1. Assembling the experimental setup

1.1) **Preparing the proximal side**

1.1.1.) 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.

1.1.2.) 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.

1.1.2.1) 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).

1.1.3.) 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.

1.1.4.) 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.

1.1.5.) 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.

1.1.6.) 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.

1.2) **Preparing the distal side**

1.2.1.) 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.

1.2.2.) 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.

1.3) **Connecting proximal and distal side**

1.3.1.) Collimate the light from the object beam exiting the MMF employing OBJ1.

1.3.2.) 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°).

1.3.3.) 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.

1.3.4.) 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.

1.3.5.) 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

2.1) **Calibrating the pixel relation between SLM and CMOS**

2.1.1.) Illuminate the whole SLM using only one of the reference beams and block the other reference and objects beams.

2.1.2.) Capture an image of the SLM with the CMOS camera.

2.1.3.) 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.

2.1.4.) Remove all beam blocks.

2.2) **Calibrating the signal paths**

2.2.1.) Block both reference beam 2 and object beam 2.

2.2.2.) 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.

2.2.3.) Remove the former beam blocks and now block both reference beam 1 and object beam 1.

2.2.4.) 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.

2.2.5.) Remove all beam blocks.

3. Transmitting the signals

3.1) Block the object beam.

3.2) 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.

3.3) Start the modulation of the input signals 1 and 2 by activating OM1 and OM2.

3.4) 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 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

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.]

Figure 3: Temporal frequency spectrum of the transmitted output signal 1 (left) and 2 (right).

Amplitude [a. u.]

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.

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DISCLOSURES:
The authors have nothing to disclose.

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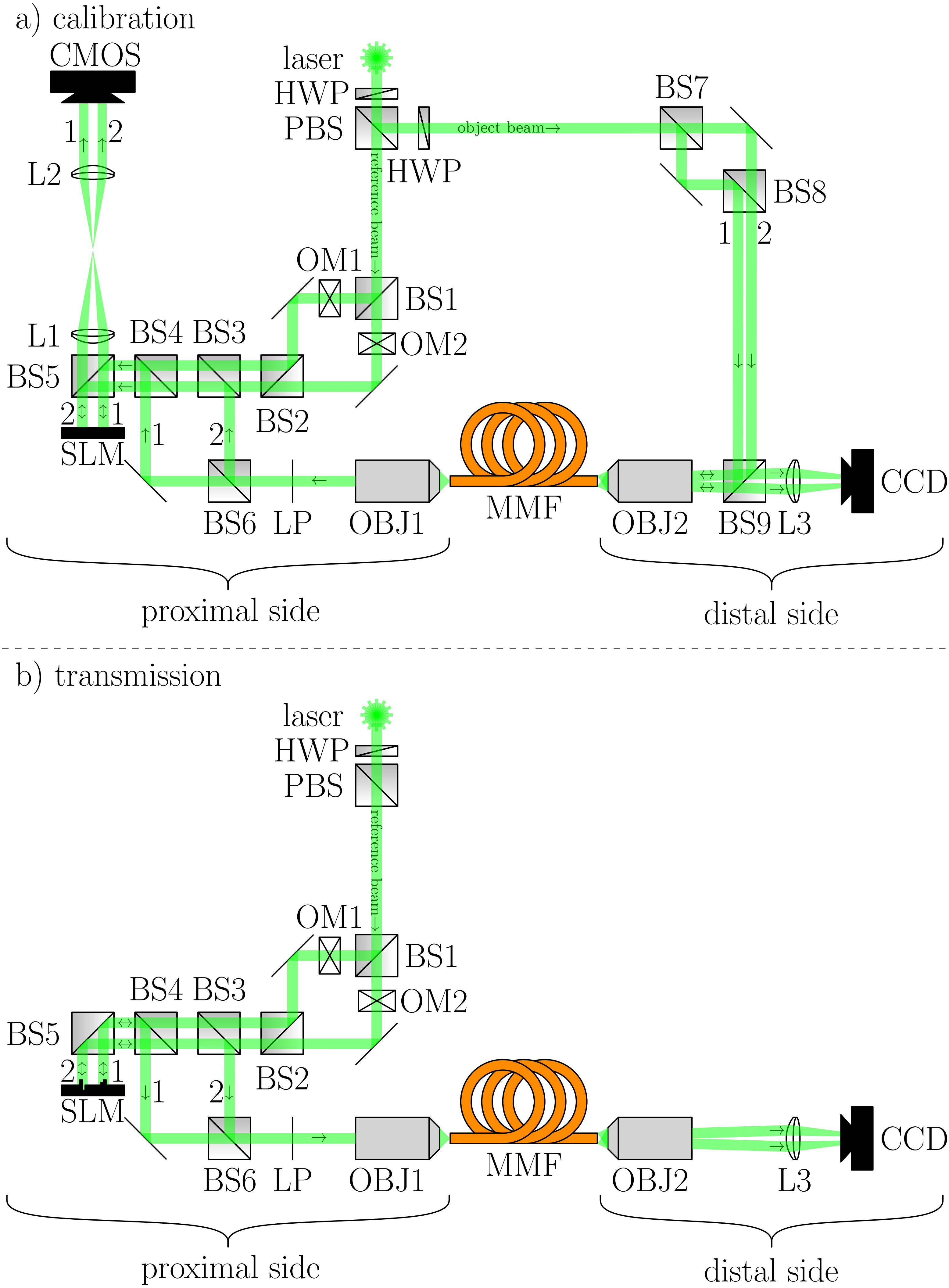

a) calibration
CMOS
laser
HWP
PBS
HWP
object beam→
reference beam→
BS7
BS8
L2
L1
OM1
BS1
OM2
BS4 BS3
BS5
BS2
SLM
BS6
LP
OBJ1
MMF
OBJ2
BS9
L3
CCD
proximal side
distal side
b) transmission
laser
HWP
PBS
reference beam→
OM1
BS1
OM2
BS4 BS3
BS5
BS2
SLM
BS6
LP
OBJ1
MMF
OBJ2
L3
CCD
proximal side
distal side

Figure 02

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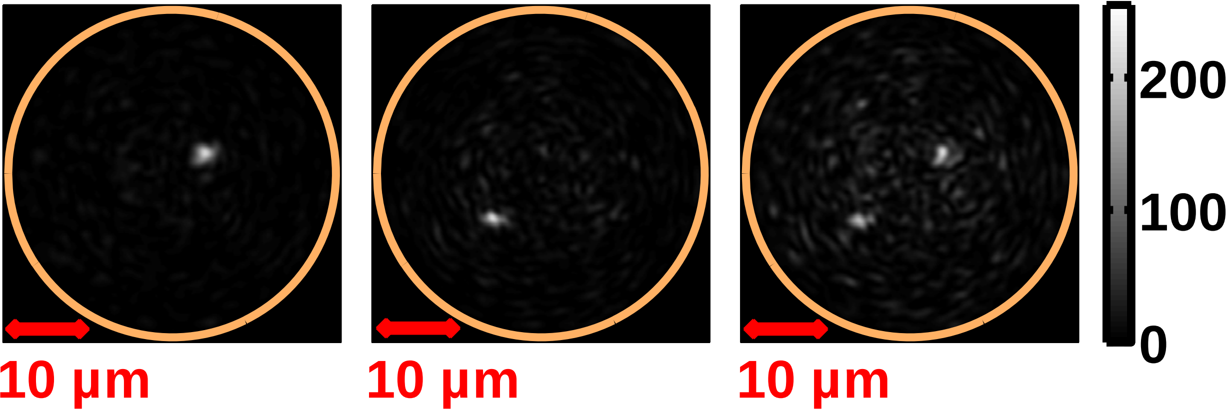

Figure 03

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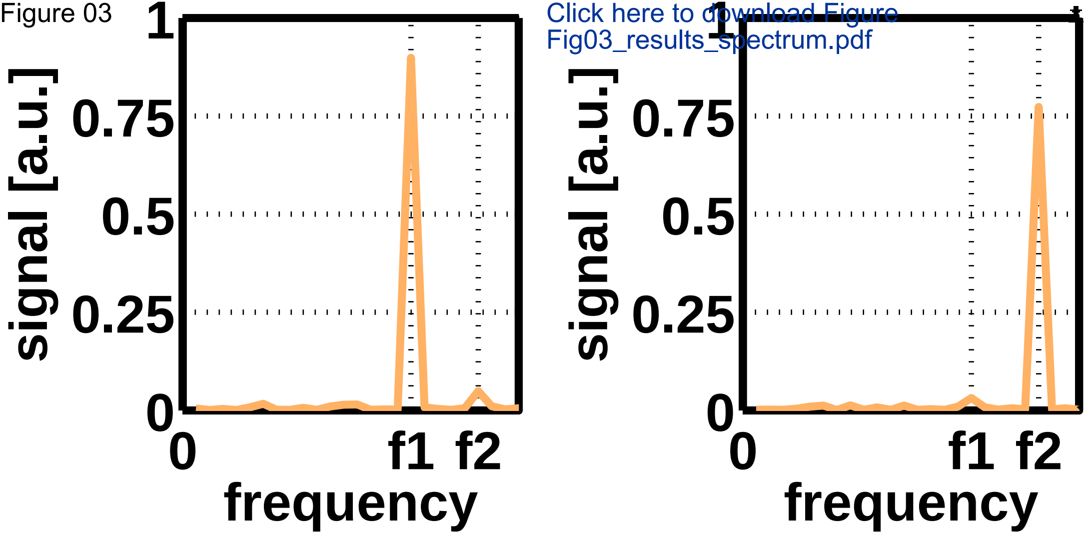

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
spatial light modulator	Holoeye	PLUTO-VIS-016	
CMOS camera	Mikrotron	MC4082	
diode-pumped solid state laser	Laser Quantum	torus 532	
CCD camera	IDS	U3-3482LE-M	CMOS camera; suitable as well
lens 1	Qioptiq	G063204000	
lens 2	Qioptiq	G063203000	
lens 3	Thorlabs	AC508-180-A-ML	
multimode fiber	Thorlabs	M14L02	
beam splitters	Thorlabs	BS013	9x
polarizing beam splitters	Thorlabs	PBS251	
mirrors	Thorlabs	PF10-03-P01	5x
microscope objectives	Thorlabs	RMS20X	2x
half wave plates	Thorlabs	WPH10M-532	2x
linear polarizer	Thorlabs	LPVISB050-MP2	
optical modulators	Thorlabs	MC2000B-EC	2x
linear and rotation stage for CMOS camera	Thorlabs	XYR1/M	
fiber connector	Thorlabs	S120-SMA	2x
reducing ring for microscope objectives	Qioptiq	G061621000	2x
xy adjustment for objective adapters	Qioptiq	G061025000	2x
z translation mount for fiber adapter	Thorlabs	SM1Z	2x
rods for fiber alignment to objectives	Qioptiq	G061210000	8x
mounts for lenses 1 and 2 plus two phantom mounts	Qioptiq	G061047000	4x
rail carriers for objective and lens mounts	Qioptiq	G061372000	6x
rail for rail carriers	Qioptiq	G061359000	2x
adapter for CCD camera to 1 post			in-house
adapter for laser to 4 posts			in-house
mount for lens 3	Thorlabs	LMR2/M	
mounts for half wave plates	Thorlabs	RSP1D/M	2x
mounts for mirrors	Thorlabs	KM100	5x
mount for linear polarizer	Thorlabs	RSP05/M	
mounts for beam splitters and SLM	Thorlabs	KM100PM/M	11x
clamping arms for beam splitters and SLM	Thorlabs	PM4/M	11x

posts for mounts, rail carriers and adapters	Thorlabs	TR75/M	29x
holders for posts	Thorlabs	PH50/M	29x
pedestals for holders	Thorlabs	BE1/M	29x
clamping forks for pedestals	Thorlabs	CF125	29x

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Cover letter to the reviewers

Manuscript ID: JoVE55407

Editor:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

=> Again, we proofread the manuscript and corrected spelling or grammar errors.

2. Please include volume, issue numbers, and DOIs for all references.

=> We have rechecked that all of the references have volume and issue numbers and added DOIs for all references.

3. For in-text formatting, corresponding reference numbers should appear as numbered superscripts after the appropriate statement(s). Please remove the brackets as well.

=> We changed the formatting of the reference numbers accordingly and removed the brackets as well.

4. Formatting:

-References should be superscript numbers without brackets in the manuscript.

=> Corrected.

-Reference section - Please include DOI where available.

=> Done.

5. Please copyedit the manuscript for grammatical errors and awkward phrasing. A subset is listed below.

-Line 38, 215 - Placement of "only" is awkward. Delete or move.

=> OK, the word "only" was deleted.

-Line 82 - Please clarify "using multiple signals being independent from each other".

=> Phrase clarified, now reads: "for multiple independent signals".

-Line 84 - "for each signal individually using only a single phase-only SLM" - please clarify

=> Phrase clarified, now reads: "individual wavefront shaping for each signal employing a single phase-only SLM".

-Line 215 – "solutions…needs"

=> OK, corrected to "solutions…need".

6. Visualization: Please provide photographic images of the setup described in Figure 1. The images should be supplied as supplemental files. Please use highlighting to indicate which sections/steps should be filmed. 2.2.2 and 2.2.4 should not be highlighted as there is insufficient detail for filming these computational steps.

=> We added two photographic images of the setup as supplemental files. As recommended, we also highlighted the part to be filmed in the protocol section of the manuscript.

7. Additional detail is required:

-1.1.2 – How is the orientation of the HWPs "adapted"? How does one adjust the power ratio? Where doe the reference and object beams come from? It is unclear what we would be filming in this step.

=> The orientation of the HWP is turned by rotating it in its rotation mount. Rotating the HWP directly affects the power ratio between reference and object beam that evolve from the polarizing beam splitter. For filming, this effect can easily be visualized by putting a screen (e.g. simply a sheet of paper) into both reference and object beam. This information was added to the paragraph.

-1.1.3 – How is the beam splitter used here? Where is it placed? How are the beams guided?

=> The beam splitter is just put into the reference beam. The incoming beam is split so that two beams result. The optical modulators OM are placed such that each of the resulting beams passes one of the OMs. For clarification, the formulations were revised here.

-1.3.3 – How is this done?

=> Like at 1.1.2.), the power of both reference and object beam should approximately equal which can be proven by putting a screen into the beams and corrected by turning the orientation of the HWP. We added the reference to 1.1.2.), here in the manuscript.

-1.3.5 – How should this look in the camera?

=> When a good contrast of the interference pattern is achieved, fringes appear in the camera image. This information was added to the manuscript.

-2.1.3 – How is a cursor chosen?

=> Simply the mouse cursor of the PC is used to obtain the coordinates, e.g. employing standard graphics software.

-2.2.1, 2.2.3 – Are the beams blocked together or separately?

=> It is only important that both of the beams are blocked at a time, thus we added the word "both" in the respective paragraphs. However, it does not matter whether they are blocked individually or with a shared beam blocker.

-3.2 – How is this done? It is unclear what actions will be filmed.

=> After two inverted phase images have been obtained, they are stitched together. The resulting image is displayed onto the SLM, typically using the computer graphics port. We enhanced the description in the manuscript accordingly. The film can show the two images as well as the stitched image on a standard computer monitor.

-3.3 – How are they activated?

=> The modulators are usually activated by pushing the "ON" button to start an on-off-modulation, but this depends on the individual control options of the modulator, thus we did not include this detail in the manuscript.

8. Results: Please discuss the results in more detail in the results section. What is the interpretation of the data presented?

=> We extended the results section and now comment on how to increase the peak-to-background ratio (PBR). Moreover, some troubleshooting in the discussion section was added for convenience. Thus, we discuss that both the CMOS camera and the SLM need at least as many pixels as modes are supported by the fiber to ensure a high PBR.

9. Discussion: Please discuss the limitations of the method. Please also expand upon the significance with respect to alternative methods – what are these other methods? Please include independent citations when discussing significance.

=> Thank you for your valuable remark. We included some further limitations of the method (coherent light source, stability of the system, group velocity dispersion). For expanded discussing of significance, we added further independent citations (11-16) at the introduction and summarized the advantages with respect to other methods at the discussion section.

Reviewer 1:

This manuscript is about phase conjugating two foci through multimode fiber. The authors used off-axis interferometry to calibrate an optimized phase mask corresponding to one signal at a time.

Then they combined two phase masks to reconstruct two foci at the same time. The manuscript itself is brief and straightforward. Considering the scope of JoVE, this manuscript can be accepted for publication. However, there are several points which need to be addressed prior to publication.

=> Thank you for your valuable remarks. We like to address all of your points in the following answers.

1. For better reproduction of the results shown in this work, I strongly suggest the authors include the section of troubleshooting. This section may include a list of problems, possible reason, and solution. Each troubleshooting can be mentioned in the procedure section.

=> Following your advice, we now describe possible reasons/solutions for a low peak-to-background ratio (PBR) in the manuscript. In our opinion, this will be the most observed problem. To achieve a high PBR, the SLM needs sufficient pixels (mode number at minimum) and the CMOS camera as well.

2. This review thinks that the manuscript can be enhanced if the authors also discuss the requirements for important parts (e.g. CCD, SLM) such that other researchers can use alternative devices. For example, the authors many want to discuss whether this scheme can also be realized with using other devices such as CMOS sensor, a dynamic mirror device, or a deformable mirror. What would be the required specification for alternative parts?

=> We appreciate your idea and included the discussion about alternatives for important parts (CMOS, CCD and SLM). The pixel number of both the CMOS and the SLM is important and should exceed the number of mode supported by the fiber. In contrast, it does not matter whether a CMOS or CCD camera is used.

3. The current manuscript missed citing relevant work. The authors should cite the following papers at least.

- Yaqoob Z, Psaltis D, Feld MS, Yang C. Optical phase conjugation for turbidity suppression in biological samples. Nature photonics 2008, 2(2): 110-115.

- Cui M, Yang C. Implementation of a digital optical phase conjugation system and its application to study the robustness of turbidity suppression by phase conjugation. Optics Express 2010, 18(4): 3444-3455.

- Čižmár T, Dholakia K. Exploiting multimode waveguides for pure fibre-based imaging. Nature Communications 2012, 3: 1027.

- Hillman TR, Yamauchi T, Choi W, Dasari RR, Feld MS, Park Y, et al. Digital optical phase conjugation for delivering two-dimensional images through turbid media. Scientific Reports 2013, 3.

- Ma C, Xu X, Liu Y, Wang LV. Time-reversed adapted-perturbation (TRAP) optical focusing onto dynamic objects inside scattering media. Nature photonics 2014, 8(12): 931-936.

- Lee K, Lee J, Park J-H, Park J-H, Park Y. One-wave optical phase conjugation mirror by actively coupling arbitrary light fields into a single-mode reflector. Physical review letters 2015, 115(15): 153902.

=> Thank you for pointing this out. We included these references (11-16) at the introduction of the manuscript, as proposed.

Reviewer 2:

Manuscript Summary:

In this manuscript a method to spatially multiplex two different signals based on ODPC is presented. Results on spatial and wavelength division multiplexing are demonstrated.

=> It is correct that spatial division multiplexing is shown, however, no wavelength division multiplexing is used but the same wavelength for both of the two signals.

Major Concerns:

I do not recommend the publication of this article unless the following comments and corrections are addressed:

=> We appreciate your concerns and addressed all of our comments.

-In long haul communications GVD is a limitation. When using a multimode fiber such as in this case, modal dispersion is quite significant. Can you elaborate in modal dispersion and mention the limitations of this approach in terms of maximum fiber length?

=> Thanks for that hint. We agree, that group velocity dispersion is a limitation of this approach for long fibers. This limitation is now mentioned at the discussion section. It can be reduced by using gradient-index fibers (instead of step-index fibers). Furthermore, spatiotemporal correction methods (see e.g. doi: 10.1038/nphoton.2011.72) are now also mentioned in the manuscript.

-The fiber length and number of fiber modes are not mentioned. As I said in the previous comment, fiber length is important, because the range of a multimode fiber approach is more limited that with single mode fibers.

=> The fiber is 2 m in length and supports up to 1710 modes. We added this information to the manuscript at the results section.

-In line 66, scattering is mentioned as the process that restricts direct transmission of images and produces light scrambling or speckle in multimode fibers. This is completely wrong. Light propagates in optical fibers as a finite number of fiber modes. Mode coupling and phase difference between the modes produced due to slight fiber bending and index of refraction imperfections is what produces the speckle like pattern.

=> We understand your point, although scattering in the strict sense means a deflection of radiation from the straight trajectory in the medium, e.g. due to non-uniform refractive index (imperfections and boundary surface between core and cladding). This also includes mode propagating and coupling. However, we changed the formulation in order to avoid possible confusion.

-In line 71 scattering is mentioned again. However in this case it is correct because the reference is about focusing light through scattering media. Just mention: "Wavefront shaping methods in scattering media..." to clarify that now you are talking about scattering media, because as it is now it seems that you are still talking about propagation in multimode fibers.

=> Thanks for pointing this out. We corrected the corresponding paragraph in the manuscript, as suggested.

Minor Concerns:

-It is not clear if the optical modulators are beam choppers.

=> In fact the modulators were simply beam choppers in our latest setup, but these can be replaced by any other kind of optical modulator, which does not affect the transmission principle itself.

-In line 190 the paragraph mention the frequency cross talk between signal 1 and 2. Why is this shown since there is already a spatial division multiplexing of the transmitted signals? The interesting thing would be to know the crosstalk of two channels delivered at the same location at two different frequencies. If the later was the case of the results shown in Fig. 3 then a clarification should be made.

=> For clarification, the signal transmission is based only on spatial division multiplexing. Thus, the two signals have to be delivered at different locations, otherwise they would overlap and could not be separated from each other. In figure 3, two different temporal frequencies f1 and f2 have been chosen for the two signals 1 and 2 two emphasize their independence. Thus, the evaluation of the received signals in frequency domain clearly shows that there is a crosstalk between both signals, since the transmitted signal 2 has also some unintended frequency content f1 from the original signal 1 and vice versa.

-In line 213, a compact fiber based implementation of the system is proposed. Since the modulation of the channels is performed with the choppers or the so called (modulators), would a fixed hologram instead of the SLM simplify the implementation of this kind of systems?

=> The SLM is needed to manipulate the light based on the inverse phase of the light propagating through the fiber. Since the behavior of fiber is usually not known or changes in time (due to bending, temperature influences), a fixed hologram cannot be used here. Anyway, this is independent from the fiber based implementation.

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