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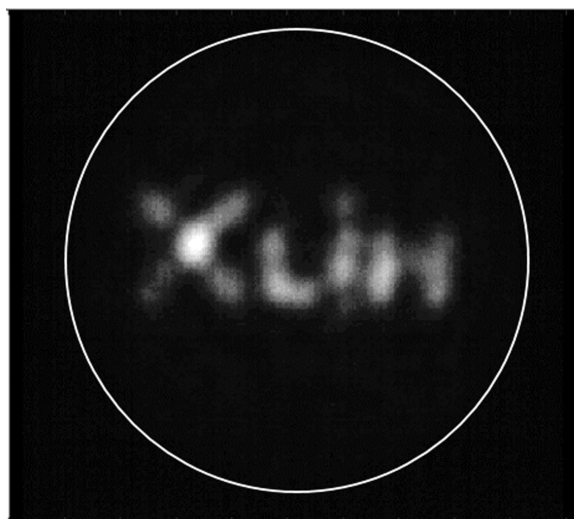
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Abstract: We report an improved scheme for the measurement of the transmission matrix of multimode waveguides in which the reference field copropagates with the signal wave. The performance of the technique is demonstrated with the measurement of a 1.6-m long multimode optical fiber guiding 104 LP modes at 1064 nm. The transmission matrix permitted efficient focusing of the light delivered at the fiber output as well as shaping in the fiber's transmission channels.

Index Terms: Multimode optical fiber, wavefront shaping, beam control.

1. Introduction

The transmission matrix (TM) is a powerful tool for the control of light wave propagation through complex linear medium [1]. Knowledge of the TM makes possible the shaping of the beam delivered through a scattering medium [2] or through a multimode waveguide with coupling [3], it makes possible as well imaging through opaque medium [4]. On a more fundamental side, TM gives data on the nature of the light transport mechanism, it permits also to derive the singular eigenmode input which leads to the highest power transmission [5]. Measured on a broad spectral range, TM allows computation of the time delay matrix and its Wigner-Smith eigenstates [6], [7] opening the space-time control of the fiber output. A difficulty in the experimental determination of the TM comes from the measurement of the output optical field amplitude and phase associated to each element of the excitation basis, since a camera records the intensity pattern only. One standard way consists in the superposition of the beam leaving the complex medium with a plane wave provided by a reference arm [3], [8], [9]. A main issue with this configuration is the interferometric stability of the reference needed on the duration of the measurement. Reference-less schemes were also implemented based on binary amplitude modulated inputs combined with phase retrieval techniques [10], [11]. Another reference-less approach, specific to multimode waveguides, relies on multiple amplitude correlations with computer generated holograms of the waveguide eigenmodes [12]. In the present letter we show that TM measurement with a co-propagating reference can be efficient, fast and well suited to the characterization of a long piece of multimode optical fiber. Although TM of bulk

scattering media (80 μm thick layer of ZnO) has been measured in a co-propagating reference scheme [2], [4] it is the first time that the technique is implemented on a long (> 1 meter) multimode waveguide.

2. Transmission Matrix Measurement of Multimode Fiber With a Common Path Reference Setup

In most cases, the input field serving to probe the sample under test is shaped in phase only by means of a spatial light modulator (SLM). In order to provide a reference, the SLM surface is divided in two sections. One fraction only of the pixels serves for the generation of the probe field by spatial phase modulation. The second fraction is kept with a uniform phase and provides the reference. In previous works on scattering media, the reference surface was chosen to cover 35% of the total SLM surface (disc shape) around a central square modulated area [2], [4]. In the experiments reported below, it was reduced to 5% only of the spatial modulator which was a fast segmented deformable mirror (SDM) with 952 actuators (Boston Micromachines KiloDM). This 5% fraction devoted to the reference represents here a trade-off between the number of degrees of freedom for the shaping and the accuracy in the TM measurement. Furthermore the 50 elementary mirrors of the SDM which served to provide a reference were randomly distributed in the cross-section. For bulk samples, a reference output field is formed by scattering of the light coming from the reference surface. In the case of waveguide, the reference output field comes from the modes excited by the light reflected by the mirror reference elements, their propagation and coupling in the waveguide and their interference at the output. In the context of multimode optical fibers, which are extremely sensitive to external perturbations, the common path reference ensures a crucial stability and accuracy in the measurement of the spatial phase delay. For each vector of the input basis (each phase chart), recovery of the phase difference between the output field and the reference was performed by the known technique of phase stepping interferometry. Setting the whole reference pixels on four different phase values successively gives four different intensity patterns at the output, from which one can compute the complex transmission of the input vector through the fiber. On the contrary to the scheme with a free-space reference for TM measurement, the reference field is unknown and is not uniform on the cross-section. As a consequence the measured phase between different pixels of a given output pattern is not meaningful. More precisely the measured TM is the product of the real transmission matrix TM_{real} by a diagonal matrix R representing the speckle field of the reference $\text{TM} = \text{TM}_{\text{real}} \times R$. However provided the reference speckle remains fixed on the duration of the recordings, the measured transmission matrix is physically relevant. It was shown in particular that the speckled reference does not impair the statistical properties of the TM and preserves the capability to focus or to image using the measured TM [2], [4].

As input basis we need an orthogonal set of input wavefronts. The number of SDM pixels is not compatible here with the choice of a binary modulated Hadamard basis. As quasi orthogonal basis, it is possible to use a set of 900 random phase distributions (for the 900 SDM elements used for wavefront shaping). We have used also the basis made up of tilted plane wavefronts and associated to a discrete sampling of the wave-vector space (34×34 samples). The beam from a CW fiber laser operating at 1064 nm was first expanded and collimated to cover the 10 mm diameter of the SDM (see Fig. 1). The modulated beam was further demagnified and imaged onto the input facet of the MMF. The MMF was a 1.6 m long piece of step index fiber, with a core diameter of 90 μm and a numerical aperture $\text{NA} = 0.102$. It carried 104 LP modes per polarization. The fiber was loosely wound and laid on the optical table. The output figure of the MMF was imaged with magnification onto a 16 bits CCD camera (FLIR Grasshopper 3). The smallest speckle grain expected on the fiber output facet is of the order of $\lambda/2 \text{NA} \sim 5.2 \mu\text{m}$, so that the fiber core diameter represents about 18 times this value. The 128×128 pixels images taken from the CCD camera were therefore fully sufficient for a good sampling and phase recovery of the output field. The 4×900 recorded images were then processed to get the transmission matrix between the input phase pixels ($M = 900$) and the pixels in the output image ($N = 16384 = 128 \times 128$) of the MMF output.

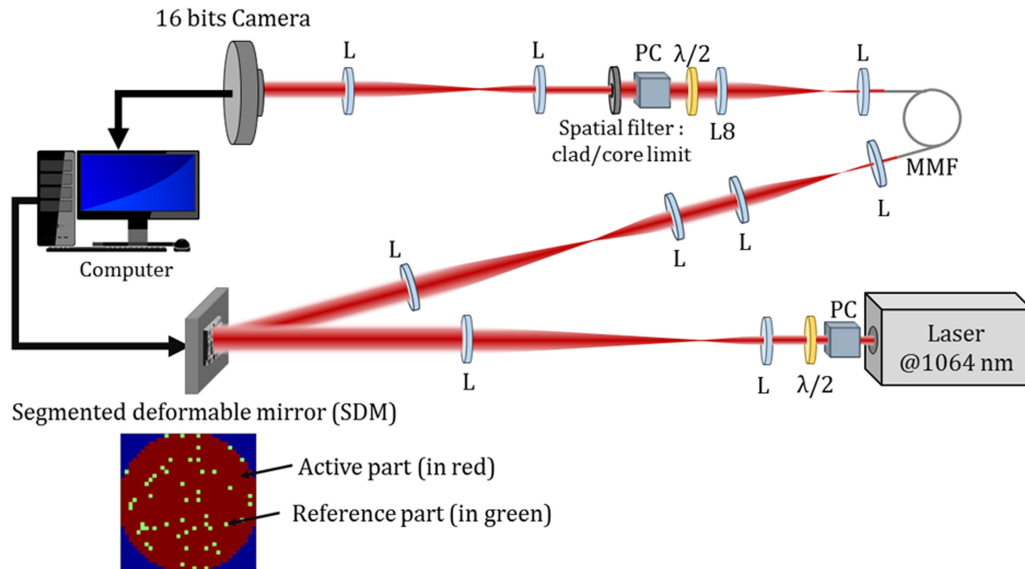


Fig. 1. Experimental set up (L: lens, PC: polarizing cube, MMF: multimode fiber). The inset shows an example of distribution of the pixels on the SDM for respectively the reference (green) and shaped input wavefront (red).

3. Results

One TM measurement takes less than one minute, a limit set by the non-optimized transmission and storing speed in the computer memory (84 frames/s). In order to evaluate the quality of the measured TM we computed the focusing operator which indicates the capability of the system to form a sharp spot (a focus) on any pixel of the fiber output cross section. Given the fact that we can shape the input phase profile only and not its amplitude, the focusing operator is given by:

$$O_{foc} = TM \cdot TM_{norm}^\dagger \quad (1)$$

with the element of TM_{norm} being normalized to their module $a_{i,j}/|a_{i,j}|$ and where the \dagger symbol denotes the conjugate transpose. Fig. 2 shows the focusing operator of our system as computed from the measured TM, after down sampling to 1024 pixels to make the display more readable. The strong peak (yellow line) on the diagonal means that the focusing should be efficient on each pixel of the fiber cross section. Because the pixel in the image is of the order of $3.3 \mu\text{m}$, i.e., smaller than the smallest speckle grain ($\sim 5 \mu\text{m}$), the focus spot which can be shaped covers a surface a little bit larger than a single pixel. That is the reason why one can see in Fig. 2(a) parallel line on each side of the diagonal (separated from the diagonal because the 2D output images are rearranged in 1D-vectors to build up the operator). Their intensity is weak but sufficient to make them visible on top of the background (see lower inset). The intensity at the focus is represented on the whole fiber core section in the upper inset of the figure, after normalization to its peak value. It shows an almost uniform efficiency demonstrating that the reference wave with a speckled structure has a weak impact.

We have checked the use of the TM for focusing through the 1.6 meter long MMF. To get a desired output field E_{out} , the input phase profile must be shaped according to:

$$E_{in} = TM^\dagger \cdot E_{out} / |TM^\dagger \cdot E_{out}| \quad (2)$$

Three typical output patterns are presented on Fig. 3. The left image of Fig. 3 was obtained with a random input wavefront and serves for reference. The middle and right images of Fig. 3 show focusing of the output beam in two different areas when the SDM shaped the input wavefront according to Equ. (2). The reference pixels were kept on (no option to switch them off) and set to

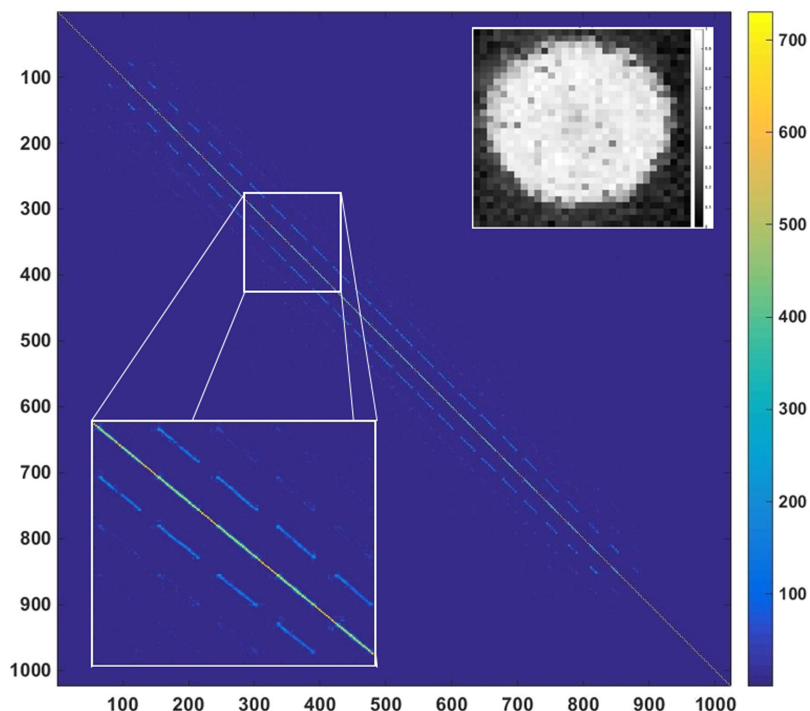


Fig. 2. Focusing operator on 1024 positions, computed from the measured transmission matrix of the MMF with a zoom on the diagonal in lower inset. Upper inset, focusing efficiency on the MMF cross-section normalized to its maximum value.

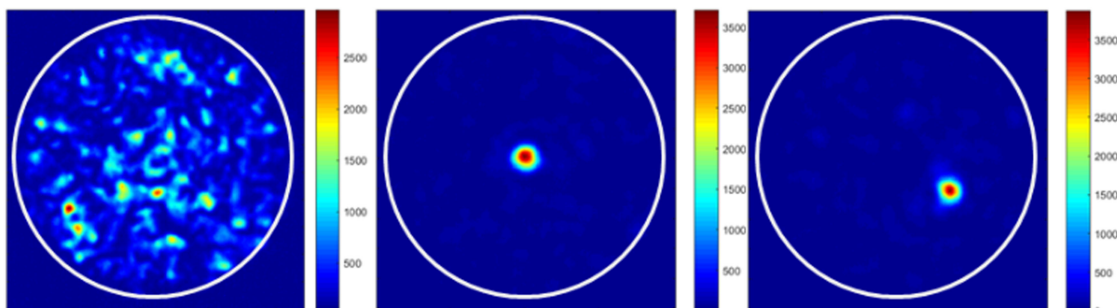


Fig. 3. Output intensity pattern obtained for a random input wavefront (left), for a wavefront shaping based on the TM to get a focus at the fiber center (middle) and then to get a focus in an off-centered area (right).

a null phase on the deformable mirror when the fiber output was shaped to a focus. The width of the quasi Gaussian focused spot shaped on the fiber output facet was measured to be $5.7 \mu\text{m}$ full width at half maximum in intensity (average on 25 positions), a value very close to the $5.2 \mu\text{m}$ of the smallest speckle grain fixed by the fiber NA.

Beam focusing through a complex medium is usually assessed by the enhancement factor η given by the ratio between the peak intensity on the focus spot I_{foc} and the average value of the background $\langle I \rangle$: $\eta = \frac{I_{foc}}{\langle I \rangle}$. We measured here an intensity enhancement value of 80.7 for a centered focus and 75.1 for the off-centered one. These values are extremely close to the value expected from theory [13] $\eta = \frac{\pi}{4} \cdot (N - 1) + 1 = 82$ (N denoting the number of freedom degrees, here given by the number of modes). Because the SDM was a fast shaping device, once the TM has been recorded, it was possible to perform a raster scanning of the output focus at a 30 kHz speed.

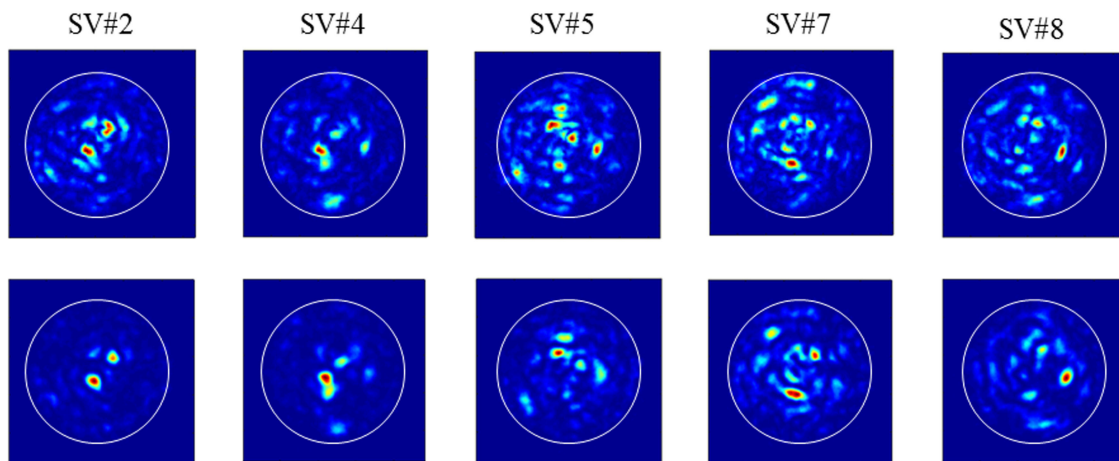


Fig. 4. Comparison between the theoretical output singular vectors computed from the SVD of the measured TM (top line) and the experimental patterns observed after shaping of the MMF input according to the input singular vectors (bottom line). A few selected singular vectors are illustrated here chosen among the ones with the ten highest singular values.

In a second step we computed the singular value decomposition (SVD) of the TM. In order to demonstrate a more complex spatial control of the MMF output that involves the elements of the full TM, we chose to shape the output field according to some singular vectors of the SVD, also known as transmission channels in the context of scattering media. Taking the output singular vectors corresponding to some of the ten stronger singular values as successive targets, we controlled the SDM so as to shape the input wavefront according to the associated input singular vectors. We provide on Fig. 4 the five expected theoretical patterns for the corresponding output singular vectors (top line) and the five patterns experimentally recorded at the fiber output (bottom line), after wavefront shaping derived from the TM SVD. The observed output figures look very close to the expected ones although the shaping of the excitation was achieved on the phase front only, keeping an overall Gaussian intensity distribution.

4. Conclusion

In conclusion, we have adapted to multimode waveguides the TM measurement scheme using a co-propagating reference. We have demonstrated that 5% of the input wavefront devoted to the reference wave is enough to preserve the dynamic required for a complex value TM measurement. Based on the TM, focusing of the laser light transmitted through a 1.6 m long MMF was achieved with performances very close (91%–98%) to the theoretical limit. The common path benefits are a simplified set-up and an improved stability for the coherent interference with the reference leading in particular to an enhanced robustness with respect to temperature variation. The technique has been further used to characterize a MMF amplifier at various gain levels where thermal effects due to the powerful pump laser were significant. Amplified beam control by use of the active fiber TM has been demonstrated and will be reported in a future paper. With an improved transmission and recording of the output images during the measurement (500 frames/s. have been already reported [7]) it should be possible to get the fiber TM in ~ 7 seconds and even faster with the acceleration provided by GPU [14].

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