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Optical memory effect in square multimode fibers

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We demonstrate experimentally the existence of a translational optical memory effect in square-core multimode fibers. We found that symmetry properties of square-core waveguides lead to speckle patterns shifting along four directions at the output for a any given shift direction at the input. A simple theoretical model based on a perfectly reflective square waveguide is introduced to predict and interpret this phenomenon. We report experimental results obtained with 532-nm coherent light propagating through a square-core step-index multimode fiber, demonstrating that this translational memory effect can be observed for shift distances up to typically 10 microns after propagation through several centimeters of fiber. © 2022 Optical Society of America

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The so-called memory effect has attracted considerable attention since the seminal work by Feng and Freund in the 80s [? ?]. In the optics community, the optical memory effect refers to the fact that the wavefront transmitted or reflected by a scattering material will tilt or shift, but otherwise not change, when the incident wavefront is tilted or shifted [? ? ? ?]. Beyond its interest for fundamental physics, as a particular class of input-output correlations, the optical memory effect have proven extremely useful to perform imaging through multiple scattering media, either by enabling calibration-free imaging methods [? ?] or by extending the range of isoplanatic patches in wavefront shaping experiments [? ?].

Highly multimode waveguides behave in many ways similarly to multiple scattering media, and many imaging methods developed to see through multiple scattering media have been adapted to perform imaging through multimode waveguides, most specifically through multimode fibers (MMFs) [? ?]. Input-output correlation through MMFs in the form of some optical memory effect would thus enable the development of calibration free imaging methods inspired from those developed for scattering media [? ?], which would revolutionize minimally invasive lensless microendoscopy. However, as opposed to thin scattering, it is generally acknowledged that there is no or limited memory effect in MMFs. Multicore fibers do exhibit a strong memory effect that can be exploited for lensless endoscopic imaging [? ?], but involve propagation in bundles of single mode fibers, with a much larger footprint than MMFs with a

comparable number of modes. In 2015, a rotational memory effect was reported for circular MMFs [?]. More recently, this rotational memory effect has further been combined with wavefront shaping to control and scan an optimized focus to achieve guided-star assisted imaging [?]. However, a 2D memory effect, required to perform calibration free imaging has to date never been reported with MMFs.

In this letter, we demonstrate the existence of a translational (shift-shift) memory effect in square-core MMFs. Although there has been pioneer research back in the seventies on imaging through square-core fibers [? ?], square core MMF remain mostly unexplored for lensless endoscopic applications. Recently, Velsink *et al.* investigated square-core optical MMFs in the context of imaging and emphasize their scrambling properties and concluded on the absence of input-output correlations [?]. In our work, we show for the first time that despite their better scrambling property, square MMFs do actually exhibit input-output correlations in the form of a translational memory effect.

We first introduce a simple theoretical model of scalar wave propagation inside a perfectly reflective square waveguide, in order to provide simple physical insights on the translational correlations that we demonstrate experimentally in square MMFs. We consider a square waveguide of dimension d consisting of four perpendicular perfectly reflective mirrors (see Fig. 1 and its animated version as Supplementary information), and we assume a monochromatic scalar wave model. Here, “perfectly reflective mirrors” stands for interfaces with a reflection coefficient $r = \pm 1$ for all possible incidence angles. Wave propagation through a perfectly reflecting waveguide from some input plane ($z = z_a$) to some output plane ($z = z_b$) may be easily predicted with an image theory approach: as illustrated in Fig. 1, any input field $E_{\text{in}}(\mathbf{r}_a)$ defined inside the square waveguide of edge size d is indeed equivalent by image theory to an infinite periodic input field in free space of period $2d$ along the two transverse axis of the waveguide. If we now consider a shifted version of the input field $E_{\text{in}}(\mathbf{r}_a; \Delta \mathbf{r}_a) = E_{\text{in}}(\mathbf{r}_a - \Delta \mathbf{r}_a)$, with $\Delta \mathbf{r}_a = (\Delta x_a, \Delta y_a)$, Fig. 1 illustrates that the four different types of mirror images define four *periodic* input patterns in free space, which each shifts in one of the four directions defined by $\Delta \mathbf{r}_a^+ = +\Delta \mathbf{r}_a$, $\Delta \mathbf{r}_a^- = (-\Delta x_a, \Delta y_a)$, $\Delta \mathbf{r}_a^{\pm} = -\Delta \mathbf{r}_a$ and $\Delta \mathbf{r}_a^{\pm} = (\Delta x_a, -\Delta y_a)$. As a consequence from shift-invariant propagation in free space, the output field corresponding to the shifted version $E_{\text{in}}(\mathbf{r}_a - \Delta \mathbf{r}_a)$ of the input field may thus also be expressed as the sum of four output patterns that each shifts in one of the four directions

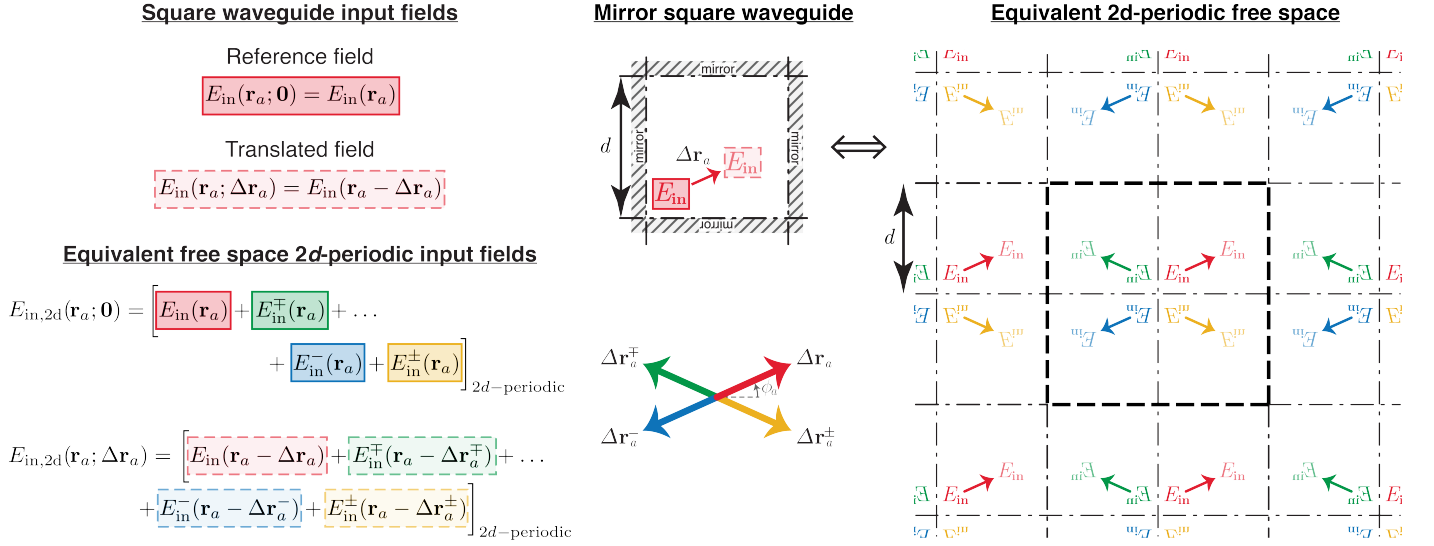


Fig. 1. Translational properties associated to a perfectly reflective square waveguide of dimension d . Based on image theory, an input field $E_{in}(\mathbf{r}_a)$ defined inside the square waveguide is equivalent to a $2d$ -periodic input field $E_{in,2d}(\mathbf{r}_a)$ defined in *free space*. This $2d$ -periodic input field consists of four $2d$ -periodic sub-fields that each undergoes a shift when $E_{in}(\mathbf{r}_a)$ undergoes a shift $\Delta\mathbf{r}_a$ (see also the animated illustration as Supplementary Information). The shift direction of each sub-field is given by one of the four possible images of $\Delta\mathbf{r}_a$ after mirror reflection on the boundary of the waveguide, noted $\Delta\mathbf{r}_a^+ = \Delta\mathbf{r}_a$, $\Delta\mathbf{r}_a^\mp$, $\Delta\mathbf{r}_a^-$ and $\Delta\mathbf{r}_a^\pm$. As a consequence, the corresponding field at the output $E_{out}(\mathbf{r}_b)$ may also be described as composed of four $2d$ -periodic fields with the same translational properties, as further described in the Supplementary Information.

76 defined above. The explicit expressions of the output field and
77 its four shifting components are provided in the Supplementary
78 information. The corresponding total intensity pattern at the
79 output plane may be derived from the field amplitude as

$$I_{out,2d}(\mathbf{r}_b; \Delta\mathbf{r}_a) = I_{out,2d}^+(\mathbf{r}_b - \Delta\mathbf{r}_a) + I_{out,2d}^\mp(\mathbf{r}_b - \Delta\mathbf{r}_a^\mp) + I_{out,2d}^-(\mathbf{r}_b - \Delta\mathbf{r}_a^-) + I_{out,2d}^\pm(\mathbf{r}_b - \Delta\mathbf{r}_a^\pm) + I_{out,interf,2d}(\mathbf{r}_b; \Delta\mathbf{r}_a) \quad (1)$$

80 Eq. 1 indicates that the intensity pattern corresponding to the
81 shift of any input field can thus be described as four shifting
82 intensity patterns on top of a non-shifting intensity pattern (resulting
83 from cross-terms interference), and defines the translational
84 optical memory effect considered in this work. While Eq. 1 is
85 valid for any type of input and output fields, we focus in this
86 work on output fields that can be described in first approximation
87 by statistically uniform speckle fields, which are naturally
88 formed by propagation through multimode fibers for mostly
89 any input field. Under the assumption that the output intensity
90 can be described as a second-order stationary speckle pattern,
91 the normalized cross-correlation between two output intensity
92 patterns corresponding to two shifted versions of a given input
93 field may be defined as:

$$C(\Delta\mathbf{r}_b; \Delta\mathbf{r}_a) = \frac{\langle \delta I_{out,k}(\mathbf{r}_b + \Delta\mathbf{r}_b; \mathbf{r}_a + \Delta\mathbf{r}_a) \times \delta I_{out,k}(\mathbf{r}_b; \mathbf{r}_a) \rangle_k}{\sqrt{\langle \delta I_{out,k}^2(\mathbf{r}_b; \mathbf{r}_a + \Delta\mathbf{r}_a) \rangle_k} \times \sqrt{\langle \delta I_{out,k}^2(\mathbf{r}_b; \mathbf{r}_a) \rangle_k}} \quad (2)$$

94 The propagation through a multimode fiber being determin-
95 istic, an ensemble of input fields is required to produce an
96 ensemble of random output fields. In Eq. 2, $\langle \cdot \rangle_k$ refers to ensemble
97 averaging of various realizations of statistically equivalent random
98 input field, and $\delta I_{out,k} = I_{out,k} - \langle I_{out,k} \rangle_k$ measures the
99 fluctuations of the intensity fields. By further assuming that the

100 four output fields can be described as four coherent *independent*
101 complex gaussian speckle fields, $C(\Delta\mathbf{r}_b; \Delta\mathbf{r}_a)$ may be expressed
102 analytically as

$$C_{analytical}(\Delta\mathbf{r}_b; \Delta\mathbf{r}_a) = \frac{1}{16} \left| \sum_{\epsilon=\{+,\mp,-,\pm\}} \mu \left(2\pi \frac{NA}{\lambda} \|\Delta\mathbf{r}_b - \Delta\mathbf{r}_a^\epsilon\| \right) \right|^2 \quad (3)$$

103 where $\mu(\theta) = \frac{2J_1(\theta)}{\theta}$ is the classical Airy pattern that describes
104 the autocorrelation of a single speckle field amplitude, and NA
105 is the numerical aperture. Predictions from Eq. ?? are plotted
106 in Fig. 2, on which the four translating components of the total
107 intensity patterns appear as four cross-correlation peaks. In
108 the Supplementary information, we provide numerical computa-
109 tions with the *exact* fields propagated through our model
110 waveguide, which confirm that Eq. ?? based on the assumption
111 of independent speckle fields fully predicts the positions and
112 amplitudes of the correlation peaks of interest. We note that for
113 the special situation where $\Delta\mathbf{r}_a$ is parallel to one of the fiber axis,
114 $\phi = 0^\circ$ for instance, one gets $\Delta\mathbf{r}_a^+ = \Delta\mathbf{r}_a^\pm$ and $\Delta\mathbf{r}_a^- = \Delta\mathbf{r}_a^\mp$, lead-
115 ing to two pairs of constructively interfering correlation peaks.
116 As a consequence, the correlation amplitude corresponding to
117 each pair of peaks is $1/4 = 25\%$ in this situation. In all other situ-
118 ations, the peak amplitude converges towards $1/16 = 6.25\%$. In
119 summary, our idealized theoretical model predicts and explains
120 the existence of a translational memory effect in the form of four
121 shifting component at the output of square waveguides, and
122 will now serve as a reference case to analyze our experimental
123 results.

124 The existence of the optical memory effect introduced theoret-
125 ically above was experimentally investigated using a step index
126 optical fiber with a square core (CeramOptec, $100 \mu\text{m} \times 100 \mu\text{m}$
127 core, NA= 0.22, length $L_{fiber} = 3 \text{ cm}$). The experimental setup is

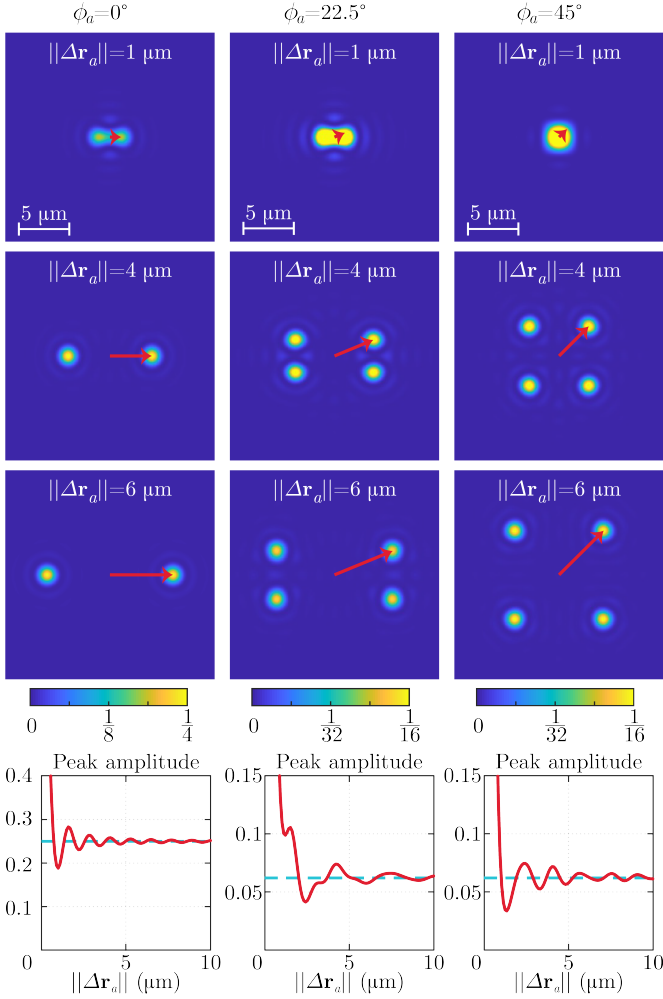


Fig. 2. Theoretical predictions for the correlation of output intensity patterns through a square waveguide for various shifts $\Delta\mathbf{r}_a$ of the input pattern. Images: $C_{\text{analytical}}(\Delta\mathbf{r}_b, \Delta\mathbf{r}_a)$ as a function of $\Delta\mathbf{r}_b$ for three values $\|\Delta\mathbf{r}_a\| = 1 \mu\text{m}$, $\|\Delta\mathbf{r}_a\| = 4 \mu\text{m}$, $\|\Delta\mathbf{r}_a\| = 6 \mu\text{m}$ and three directions $\phi_a = 0^\circ$, $\phi_a = 22^\circ$, $\phi_a = 45^\circ$; $\Delta\mathbf{r}_a$ are depicted by red arrows. Curves: amplitude of $C_{\text{analytical}}(\Delta\mathbf{r}_b, \Delta\mathbf{r}_a)$ at the expected location of the (+) peak. The blue dashed line on the graphs represents the limit value for each case, $1/4$ for $\phi_a = 0^\circ$, $1/16$ for $\phi_a = 22^\circ$ and $\phi_a = 45^\circ$.

depicted on Fig. 3, and is further detailed in the Supplementary Information, along with movies showing the input and output patterns during a scan. The data processing method to derive cross-correlations $C_{\text{exp}}(\Delta\mathbf{r}_b; \Delta\mathbf{r}_a)$ from experimental data, in consistence with the theoretical expression 2, is also detailed in the Supplementary Information. All the cross-correlation were computed from measurements inside a fixed square region of interest (ROI), as illustrated on Fig. 3.c.

Fig. 4 shows the cross-correlations $C_{\text{exp}}(\Delta\mathbf{r}_b; \Delta\mathbf{r}_a)$ obtained from the measured output intensity patterns, for various values of the translation distances $\|\Delta\mathbf{r}_a\|$ (1, 4 and 6 μm) and directions ϕ_a (0° , 22.5° and 45°). Importantly, these results correspond to $C_{\text{exp}}(\Delta\mathbf{r}_b, \Delta\mathbf{r}_a)$ computed from a *single* realization of the input speckle spot (see Fig. 3.b and section I.B of Supplementary Information). As the major result of our work, the cross-correlations obtained from the measured output speckle intensity patterns

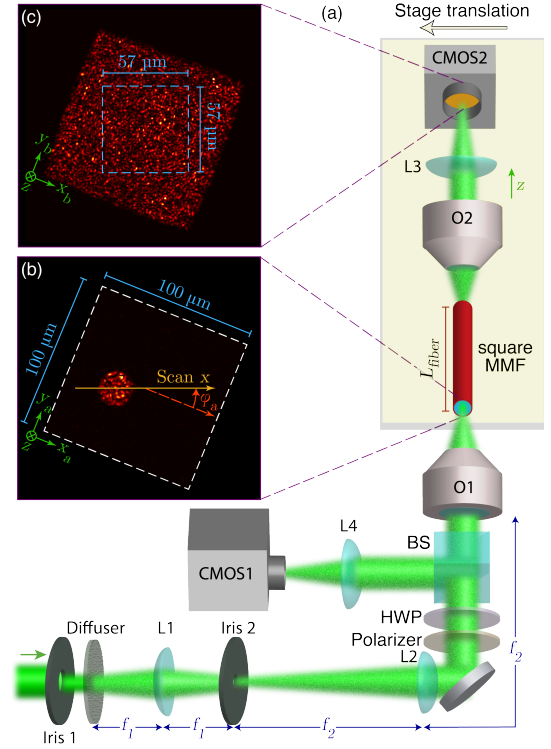


Fig. 3. (a) Experimental setup (further detailed in the Supplementary information). A coherent 532 nm beam is sent through a diffuser to create a speckled circular spot at the square fiber input. The MMF square fiber ($L_{\text{fiber}} = 3 \text{ cm}$) and all following elements are held on a motorized translation stage to translate the input field relatively to the input facet. Cameras CMOS1 and CMOS2 respectively monitor the input (b) and output intensity patterns (c).

exhibit four peaks translating away from the center as the input shift increases, following the predictions from our idealized model. In the particular case $\phi_a = 0^\circ$, only two peaks of much stronger amplitude are visible, in agreement with the theoretical predictions. To compare more quantitatively the experimental results to the theoretical predictions, the amplitude and position of each correlation peak as a function of input shift were measured via a tracking approach, and are reported in Fig. 5. For short translation distances, but large enough such that the correlation peaks can be resolved ($\|\Delta\mathbf{r}_a\| \gtrsim 1 \mu\text{m}$), the measured peak amplitudes are on the same order as that predicted by the model. The positions of the four peaks are exactly those predicted from the theory, within the accuracy of the position tracking method. The oscillations resulting from the interference between the correlation peaks predicted by the theory for small shifts are also observed experimentally.

While the positions of the correlation peaks are exactly those predicted by our simple model, their amplitude decays and vanishes into the background for shifts on the order of 10 μm (see also movies as Supplementary Information), indicating that the observed translational memory effect has a limited range. A number of reasons may explain this limited range, which include the nature of the boundary conditions at the core cladding interface (different from that of a perfect mirror) and potential fiber geometrical imperfection (fiber twist, fiber bending, rounded corners) as compared to the idealized square geometries.

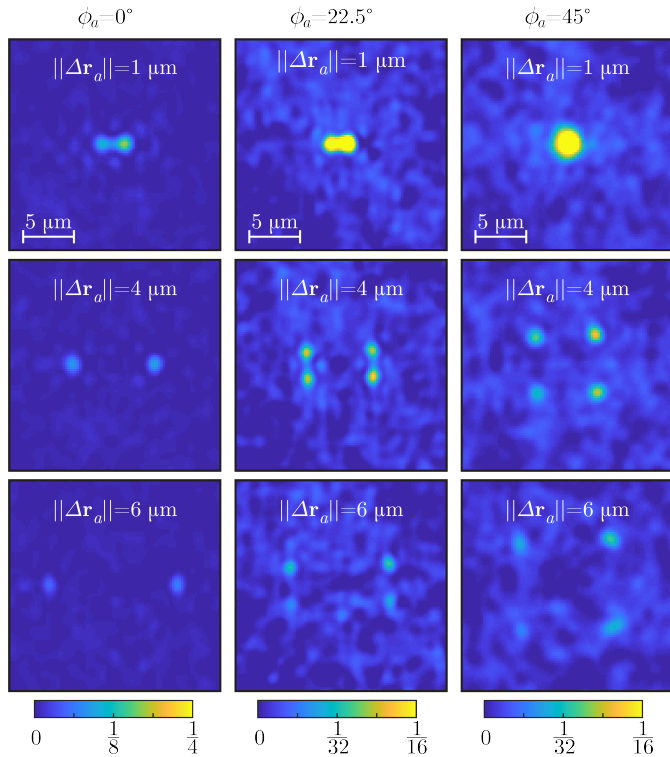


Fig. 4. Experimental results. Cross-correlations of the speckle patterns measured at the output of a 3 cm-long step-index square-core multimode fiber, obtained for various translation distances $\|\Delta\mathbf{r}_a\|$ (1, 4 and 6 μm) and directions ϕ_a (0° , 22.5° and 45°) of *one given* input pattern.

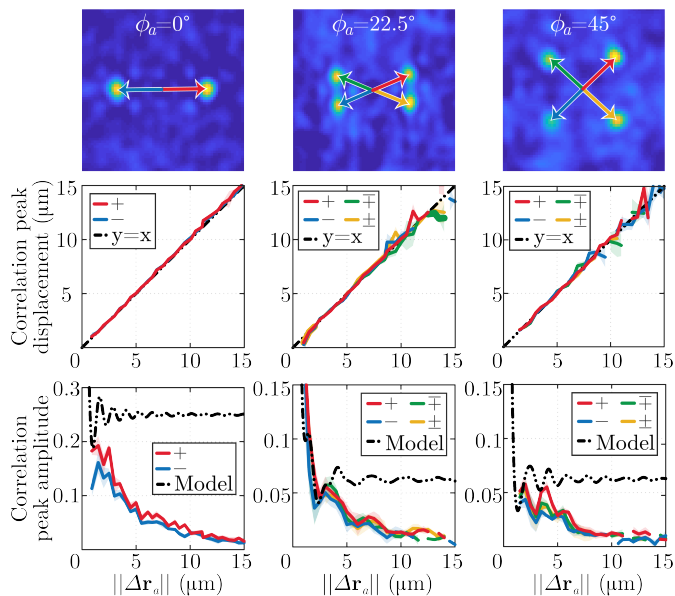


Fig. 5. Experimental results. Graphs: displacement and amplitude of the correlation peaks as a function of the input shift $\|\Delta\mathbf{r}_a\|$, for three translation direction ϕ_a (0° , 22.5° and 45°). The images correspond to experimental cross-correlations obtained for $\|\Delta\mathbf{r}_a\| = 4 \mu\text{m}$.

170 try. The purpose of our idealized model was limited to provide
 171 some physical understanding of the observed effect, as well as
 172 to provide upper bounds on the amplitude of the correlation
 173 peaks. Further investigations are required to explain and predict
 174 theoretically the observed finite range, likely by taking into ac-
 175 count more realistic boundary condition and light polarization
 176 beyond the simple scalar model considered here. All the results
 177 presented here involved a linear polarization parallel to an edge
 178 of the fiber core. However, we also obtained similar results
 179 with other directions of the linear polarization (such as parallel
 180 or perpendicular to the translation direction), indicating that
 181 the observed memory effect is not strongly influenced by the
 182 polarization. Very interestingly, preliminary experiments with
 183 different fiber lengths up to 20 cm, and with significant fiber
 184 twists, indicate that the effect is robust, with a rather constant
 185 range for the memory effect.

186 In conclusion, we demonstrated experimentally the existence
 187 of a translational (shift-shift) memory effect in square multimode
 188 fibers, and proposed a simple idealized model that predicts and
 189 explains the origin of the observed effect. Much like the classical
 190 memory effect has been exploited to perform calibration-free
 191 imaging through a scattering medium, we envision that this new
 192 type of input-output correlation will be exploited for calibration-
 193 free imaging through square multimode fibers. While our ex-
 194 perimental demonstration was performed here in optics in the
 195 visible range, our theoretical predictions are limited neither to
 196 this range nor to the field of optics, but are expected to apply to
 197 a wider range of situations including radio-frequency electro-
 198 magnetic waves and acoustic waves in square waveguides.

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