Master 2 Internship / Ph.D. Proposal

Invariant Properties in Multimode Fibers for Imaging Applications

Laboratory:

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Goal:

The goal of this internship is to study and harness invariant properties of MMFs to allow retrieving images through a fiber without having to fully characterize the system.

Context and motivations:

The control of light propagation in optical multimode fibers is an active and fast-growing field of research. Unlike single mode fibers, multimode fibers are optical waveguides that allow many trajectories, or modes, to propagate. For this reason, they are currently intensively studied for optical telecommunications and for endoscopic applications. Indeed, taking advantage of the spatial degrees of freedom would allow increasing significantly the number of channels for communications applications, similarly to MIMO (Multiple-Inputs / Multiple-Outputs) systems deployed for wireless communications. At the same time, researchers investigate the way to control and study light propagation in multimode fibers for their use as minimally invasive endoscopic imaging devices [1, 2], allowing us to improve resolutions compared to classical endoscopes using fiber bundles.

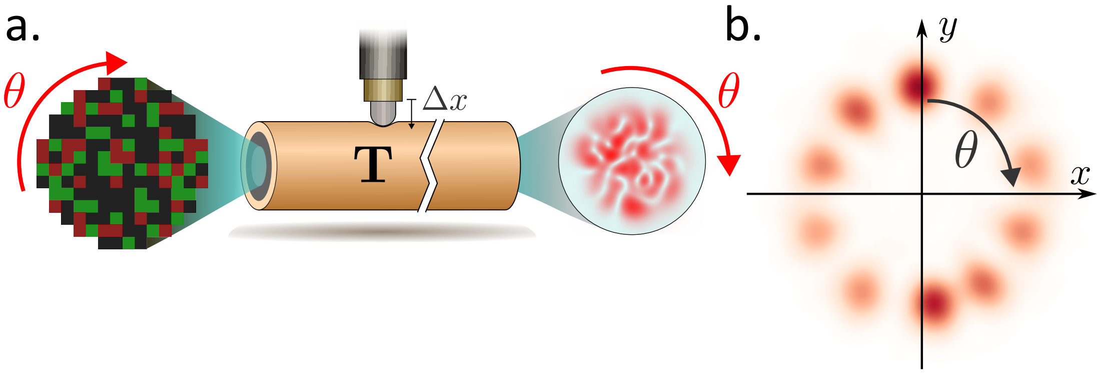

Figure 1: **Illustration of the rotational memory effect. a**. Principle. Rotating the input excitation pattern of a multimode fiber rotates the output speckle pattern. **b**. Rotation of a focal spot. After learning to focus at one output position, rotating the input pattern rotates the position of the focal spot along the axis of the fiber. Image adapted from [3].

In each instance, the reformation of a signal or an image presents a challenge due to the dispersion and unpredictability inherent in light propagation. The randomness stems from existing faults in the system as well as the fiber's geometry, such as bending, twisting. An immediate ramification of this is that an image introduced to a multimode fiber yields a seemingly random pattern at the output. This resulting pattern displays no resemblance to the original input.

A first approach to reconstruct a signal or an image is to learn the transmission matrix [4], which describes the link between the input and the output of an optical system, using the technique we developped at the Langevin Institute for scattering media [5]. We recently demonstrated that we can use this matrix to find channels insensitive to strong deformations [6]. However, it requires to have access to both sides of the system for the calibration, which can be difficult to obtain and that is only valid as long as the system does not change.

In scattering media, that also scrambles input light, there exist invariant properties that can help us to retrieve information about an input image without the need to know the full transmission matrix. A good example is the angular memory effect, which postulates that for a given illumination, regardless of the unknown nature of the resulting random pattern, a shift in the input illumination translates into a shift the output speckle pattern with minimal deformation. Exploiting this phenomenon has opened up the groundbreaking opportunity to recover fluorescent imagery of objects hidden behind a thick scattering medium [7].

In multimode fibers, a similar phenomenon, illustrated in Fig. 1 and dubbed as the rotational memory effect (RME), has been observed [8]. We recently elucidated this phenomenon by providing a theoretical framework and by showing that the potential of this effect can be substantially enhanced [3].

The objective of this project is to find and study invariant properties in multimode fiber in order to improve imaging capabilities of current systems. The ultimate goal is to lift the need for calibration to allow one-shot imaging through a multimode fiber for real-time imaging in biological samples.

Preliminary results:

For low disordered fibers, which is the case for short (few centimeters to few tenths of centimeters) systems used for endoscopic applications, one can use *a priori* information about the statistics of the transmission matrix, even when the actual matrix is not known. If we add some known statistical properties, or other priori knowledge about the image, which is usually available for microscopy, we can reconstruct the image without calibration. We developed an algorithm adapted from sparse blind deconvolution algorithms [9], that allows, in simulation, reconstructing images from the output speckle pattern in one shot, taking advantage of the rotational memory effect, even if the fiber changes over time (see Fig 2).

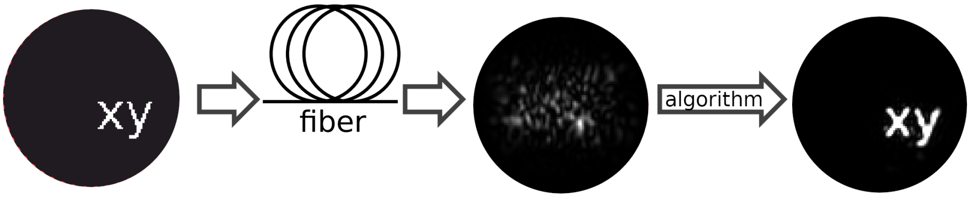

Figure 2: Results of the simulations using the *sparse blind deconvolution* for calibration-free imaging through a multimode fiber. Input intensity object (left), output speckle intensity pattern (middle) and reconstructed image (right).

Project description:

Taking advantage of the expertise of the Langevin Institute in the theory and experimental control of light propagation in complex media [10, 5, 11] and multimode fibers [4], the student will use wavefront shaping techniques to study and measure invariant properties in multimode fibers. In particular, we will investigate the analogy between scattering media and multimode fiber to take advantage of known results and tools developed in this field and apply them to optical fibers. On the experimental side, we will characterize transmission matrices of multimode fiber systems to highlight and charaterize the invariant properties. Using custom made algorithms, and taking advantage of fast optimized deep learning frameworks (pyTorch [12, 6]), we will transpose and improve the concept demonstrated in simulations and develop new approaches for calibration-less imaging through multimode fibers.

Applicant profile:

The applicant is expected to have a taste for wave physics, theory, and code. The internship will require an extensive use of Python for interfacing, data acquisition, post-processing and image reconstruction algorithms.

TL;DR:
We will play with deep learning frameworks to develop new approaches for calibration-less imaging through multimode fibers based on the study of invariant properties in multimode fibers.

References:

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