Ph.D. Position:

Invariant Properties in Multimode Fibers for Imaging Applications

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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 [1, 2, 3]. 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 [4, 5, 6], allowing to improve resolutions compared to classical endoscopes using fiber bundles.

In both cases, the reconstruction of a signal or an image is difficult because of the presence of dispersion and randomness of light propagation. Randomness arises from to the existence of defects and the geometry of the fiber (bending, twisting, etc.). A direct consequence is that an image at the input of a multimode fiber results in a seemingly random pattern at the output that bears no resemblance to the input one.

A first approach to reconstruct a signal or an image is to learn the transmission matrix [7], 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 [8]. 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.

However, as in multiple 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 existence of a *rotational memory effect* for weakly disordered fibers. It implies that if one can learn how to focus on one point of the fiber, by rotating the input wavefront, one can scan all the points on a circle (Figure 1.). It allows us to scan the output facet of the fiber with only limited information.

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.

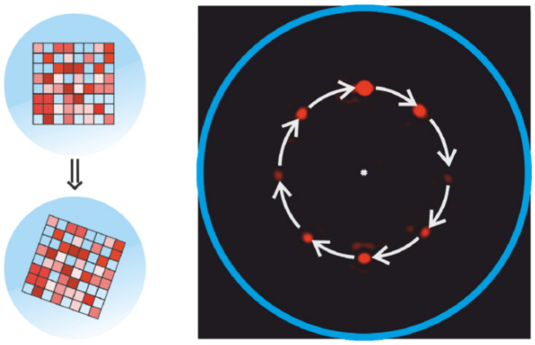

Figure 1: Illustration of rotational memory effect. By rotating the input mask that focuses light at one output position, we focus light at another position on a circle. Image from [9].

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 [10], that allows, in simulation, reconstructing images from the output speckle pattern in one shot, even if the fiber changes over time (Figure 2.).

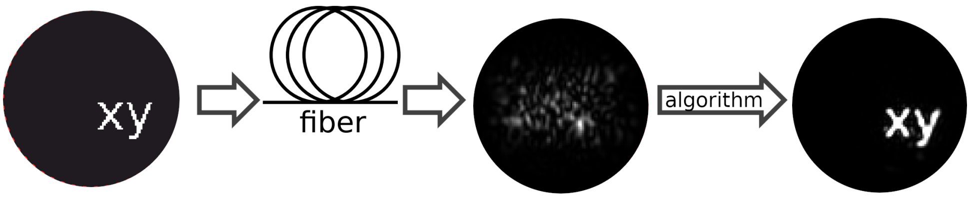

Figure 2: Results of the simulations using the *sparse blind deconvolution* for calibration-free imaging through a multimode fiber. Input intensity object (left), output speckle intensity pattern (middle) and reconstructed image (right).

Project description

Taking advantage of the expertise of the Langevin Institute in the theory and experimental control of light propagation in complex media [11, 8, 12] and multimode fibers [7], 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, we will transpose the concept demonstrated in simulations for calibration-less imaging through multimode fibers.

References:

[1] R. Ryf et al. Mode-division multiplexing over 96 km of few-mode fiber using coherent 6 6 mimo processing. *J. Lightwave Technol.*, 30(4):521–531, 2012.

[2] S.G. Leon-Saval, N.K. Fontaine, J.R. Salazar-Gil, B. Ercan, R. Ryf, and J. Bland-Hawthorn. Mode-selective photonic lanterns for space-division multiplexing. *Opt. Express*, 22(1):1036–1044, 2014.

[3] J. Carpenter, B.J. Eggleton, and J. Schroder. Applications of spatial light modulators for mode-division multiplexing. *ECOC Proc.*, 2014.

[4] T. Cizmar and K. Dholakia. Exploiting multimode waveguides for pure fibre-based imaging. *Nature Commun.*, 3, 2012.

[5] D. Kim, J. Moon, M. Kim, T.D. Yang, J. Kim, E. Chung, and W. Choi. Pixelation-free and real-time endoscopic imaging through a fiber bundle. *Opt. Lett.*, 39(7), 2014.

[6] M. Ploschner, T. Tyc, and T. Cizmar. Seeing through chaos in multimode fibres. *Nature Photonics*, 9(8), 2015.

[7] M.W. Matthès, P. del Hougne, J. de Rosny, G. Lerosey, and S.M. Popoff. Optical complex media as universal reconfigurable linear operators. *Optica*, 6, 04 2019.

[8] S.M. Popoff, G. Lerosey, M. Fink, A.C. Boccara, and S. Gigan. Image transmission through an opaque material. *Nature Commun.*, 1:81, 2010.

[9] Lyubov V. Amitonova, Allard P. Mosk, and Pepijn W. H. Pinkse. Rotational memory effect of a multimode fiber. *Optics Express*, 23(16):20569, jul 2015.

[10] Daniel L. Marks, Okan Yurduseven, and David R. Smith. Sparse blind deconvolution for imaging through layered media. *Optica*, 4(12):1514, dec 2017.

[11] S.M. Popoff, G. Lerosey, R. Carminati, M. Fink, A.C. Boccara, and S. Gigan. Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media. *Phys. Rev. Lett.*, 104.

[12] D. Andreoli, G. Volpe, S.M. Popoff, O. Katz, S. Gresillon, and S. Gigan. Deterministic control of broadband light through a multiply scattering medium via the multispectral transmission matrix. *Sci. Rep.*, 5, 2015.