D. Ancora, D. Di Battista, A. M. Vidal, S. Avtzi, G. Zacharakis, and A. Bassi, "Phase Retrieval for Hidden Tomography Reconstruction," in Imaging and Applied Optics Congress, OSA Technical Digest (Optical Society of America, 2020), paper JW5A.1.

https://doi.org/10.1364/3D.2020.JW5A.1

Phase Retrieval for Hidden Tomography Reconstruction

Daniele Ancora[1*], Diego Di Battista[2], Asier Marcos Vidal[3], Stella Avtzi[2,4], Giannis Zacharakis[2], Andrea Bassi[1,5]

[1] *Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*
[2] *Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, N. Plastira 100, 70013 Heraklion, Greece*
[3] *Dept. of Bioengineering and Aerospace Engineering, Universidad Carlos III de Madrid, 28911 Leganés, Spain*
[4] *Institut de Ciències Fotòniques, Barcelona Institute of Science and Technology, Av. C. F. Gauss 3, 08860 Castelldefels, Spain*
[5] *Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

**email to: daniele.ancora@polimi.it*

Abstract: We discuss the problem of tomographic reconstruction of fluorescent objects hidden behind random media. To accomplish this, we focus on the properties of the auto-correlation, relying on phase retrieval algorithms to perform 3D reconstruction.

1. Introduction

Imaging [1] and focusing [2] through disordered structures has recently caught the attention of researchers working in the field of optical imaging, providing new ways to peak inside biological structures or complex media. In particular, the statistical properties inherently retained in the speckle's auto-correlation have enabled tunable lensing properties [3, 4] and imaging capabilities [1, 5] at optical wavelengths. We introduce a new tomographic approach for the reconstruction of a three-dimensional fluorescent object located behind a scattering layer. Using a previously confirmed theoretical assumption, relying on the auto-correlation of the speckle pattern, we demonstrate that a tomographic reconstruction can be achieved. We acquire an auto-correlation sequence, that can be inverted by the means of phase retrieval protocols and a modified back projection algorithm, obtaining a faithful reconstruction of the hidden object [6].

2. Materials and methods

Let us consider the case of a three-dimensional fluorescent object, $O(x,y,z)$, incoherently emitting behind a generic scattering slab. A camera, placed on the other side, can record only the intensity field that propagated through the disordered layer and has no access to its direct imaging. A sketch and further details of the experimental setup can be found in our main work [6]. In this configuration, the camera sees a seemingly disordered intensity distribution, better known as speckle pattern S, like the one shown in Fig. 1A). Under isoplanatic conditions, also called the memory-effect regime [1, 3], such pattern is determined by the convolution between a random point-spread-function (PSF) introduced by the scattering layer and the object emitting behind it. The opaque layer acts as a disordered optical element in a classical sense and the speckle pattern may resemble a shuffled superposition of object's projections randomly located in space. Since our object of interest is three-dimensional, this concept may be extended at any rotation angle φ at which we observe the scrambled field S_φ, that contains the underlined object's projection O_φ. Interestingly, if the opaque object is completely random, the auto-correlation of the PSF is a sharply peaked function, thus $PSF \star PSF = \delta$. This suggests the following chain of relations:

$$S_\varphi \star S_\varphi = \left(O_\varphi * \mathrm{PSF}_\varphi\right) \star \left(O_\varphi * \mathrm{PSF}_\varphi\right) = \left(O_\varphi \star O_\varphi\right) * \left(\mathrm{PSF}_\varphi \star \mathrm{PSF}_\varphi\right) = O_\varphi \star O_\varphi. \quad (1)$$

This implies, under memory-effect conditions, that the auto-correlation of the speckle pattern matches the auto-correlation of the object hidden behind it. For better clarity, we report the results of the measurement of an object composed by two -separated- fluorescent structures. The auto-correlation calculated from the speckle pattern in Fig. 1A) is shown in Fig. 1B), for the angle $\varphi = 0$. Here we can notice that χ_φ has a well defined structure, implying that an apparently random intensity sequence still retains information about the object secreted behind it. The result of the calculation χ_φ at any rotational angle $\varphi = 0, 2\pi$ gives rise to the so-called sinogram in Fig. 1C), where each auto-correlation was stacked one after the other and looked from above as a function of the angle φ. The auto-correlation sinogram is crucial for a correct reconstruction of the object without relying on any

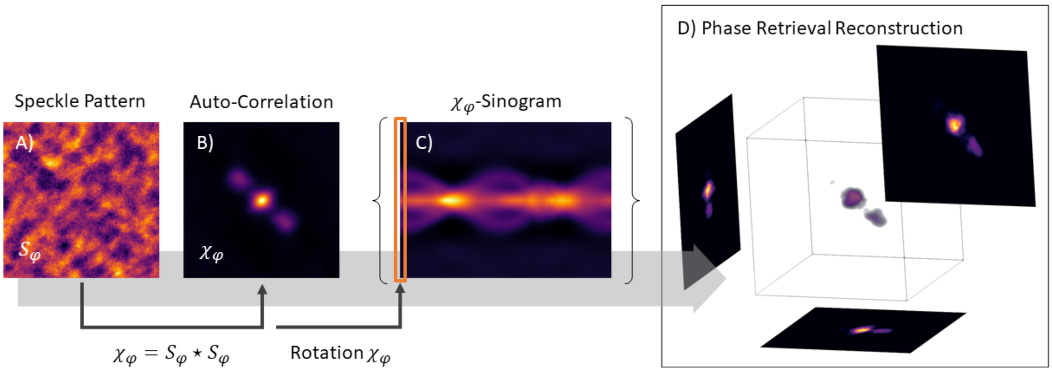

Fig. 1. A) Speckle pattern produced by the light-propagation through a scattering media from an unknown object. B) Auto-correlation of the speckle pattern shows the presence of structural information. C) Sinogram obtained by stacking auto-correlation from different angular measurement. D) Final reconstruction of the object after sinogram-inversion and phase retrieval.

alignment procedure [7], as it was also proven in direct imaging with selective plane illumination microscopy [8]. The χ_φ-sinogram in fact, can be inverted via back-projection algorithms (such as inverse Radon transform) in order to obtain a tomographic reconstruction for the three dimensional auto-correlation χ of the object [6]. Once obtained an estimate for χ, it is possible to feed this quantity into a phase retrieval algorithm [9] that solves the inverse problem of finding the phase connected to the Fourier modulus of the object. In fact, this quantity can be easily estimated by $\|\mathscr{F}\{O\}\| = \sqrt{\mathscr{F}\{\chi\}}$, thanks to the Fourier-spectrum theorem. Once retrieved the phase, the reconstruction is made possible by a simple inverse Fourier transform. We render the result of the reconstruction of the sample considered in Fig. 1D), along with its axial maximum projections along the three views.

3. Discussion and Conclusion

We have discussed how it is possible to extend the concepts of computed tomography in the field of hidden imaging. Without the use of a lens system, we observe that three-dimensional features were correctly recovered by only looking at scrambled speckled intensity of an unknown object hidden behind a scattering layer. This may open new paths to be exploited in disordered photonics, with potential applications in high-resolution tomography even in the case of strong light-scattering scenarios.

Acknowledgments. H2020 Marie Skłodowska-Curie Actions (HI-PHRET project, 799230); H2020 Laserlab Europe V (871124).

References

1. J. Bertolotti, E. G. Van Putten, C. Blum, A. Lagendijk, W. L. Vos, and A. P. Mosk, "Non-invasive imaging through opaque scattering layers," Nature **491**, 232 (2012).
2. I. M. Vellekoop, A. Lagendijk, and A. P. Mosk, "Exploiting disorder for perfect focusing," Nat. Phot. **4**, 320 (2010).
3. D. Di Battista, D. Ancora, H. Zhang, K. Lemonaki, E. Marakis, E. Liapis, S. Tzortzakis, and G. Zacharakis, "Tailored light sheets through opaque cylindrical lenses," Optica **3**, 1237–1240 (2016).
4. D. Di Battista, D. Ancora, M. Leonetti, and G. Zacharakis, "Tailoring non-diffractive beams from amorphous light speckles," Appl. Phys. Lett. **109**, 121110 (2016).
5. O. Katz, P. Heidmann, M. Fink, and S. Gigan, "Non-invasive single-shot imaging through scattering layers and around corners via speckle correlations," Nat. Phot. **8**, 784 (2014).
6. D. Ancora, D. Di Battista, A. M. Vidal, S. Avtzi, G. Zacharakis, and A. Bassi, "Hidden phase-retrieved fluorescence tomography," Opt. Lett. **45**, 2191–2194 (2020).
7. D. Ancora, D. D. Battista, G. Giasafaki, S. E. Psycharakis, E. Liapis, J. Ripoll, and G. Zacharakis, "Optical projection tomography via phase retrieval algorithms," Methods **136**, 81 – 89 (2018).
8. D. Ancora, D. Di Battista, G. Giasafaki, S. E. Psycharakis, E. Liapis, J. Ripoll, and G. Zacharakis, "Phase-retrieved tomography enables mesoscopic imaging of opaque tumor spheroids," Sci. Rep. **7**, 11854 (2017).
9. Y. Shechtman, Y. C. Eldar, O. Cohen, H. N. Chapman, J. Miao, and M. Segev, "Phase retrieval with application to optical imaging: a contemporary overview," IEEE Signal Process. Mag. **32**, 87–109 (2015).