

MASTER 2 AND DOCTORAL THESIS PROPOSAL (Academic year 2026 - 2027)

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 Collaboration with Institut de la Vision (Prof. Gilles Tessier' group).
 Thesis possibility after internship: YES

POLARIZATION-RESOLVED 3D HOLOGRAPHIC IMAGING OF SECOND-HARMONIC GENERATION **IMAGERIE HOLOGRAPHIQUE 3D RESOLUE EN POLARISATION DE LA GENERATION DE SECONDE HARMONIQUE**

Keywords : *Holography, Second-Harmonic Generation, Nonlinear Optics, Interferometry, Polarization, Plasmonics, Nanophotonics, Biology Imaging*

Description of the work : 50% experimental, 50% numerical/processing (to be discussed)

Summary: **This project aims at characterizing second-harmonic generation (SHG) emitted by various samples with a single-shot and three dimensional (3D) measuring technique called holography. Through the measurement of the field's phase and amplitude, algorithmic propagation allows to retrieve the full radiation pattern from objects such as plasmonic nonlinear nanoantennas, including plasmonic, dielectric, and hybrid nanostructures, or such as biological samples that exhibit strong nonlinear responses. Combined with polarization multiplexing, the system will simultaneously record multiple polarization components and reconstruct numerically their individual 3D distributions in real space.**

Second-harmonic generation (SHG) is a nonlinear optical process in which two photons at angular frequency ω are coherently converted into one photon at 2ω . SHG is forbidden in the electric-dipole approximation in centrosymmetric media and is generally absent in isotropic amorphous materials, making it a powerful probe of non-centrosymmetric structures. Importantly, the coherent nature of SHG makes it particularly well suited to interferometric systems, a potential that remains relatively underexplored in the field of optical microscopy.

In this project, we aim to further develop a holographic imaging system in which SHG emitted by a sample under femtosecond laser excitation interferes with a reference SHG field generated in a frequency-doubling crystal of beta-barium borate (BBO). By recording the resulting holograms with an EM-CCD camera, we can retrieve the amplitude and phase of the optical field and numerically back-propagate it to reconstruct three-dimensional (3D) SHG images and radiation patterns [1].

Our first SHG holography experiments allowed us to obtain already two key results [2]. First, despite the short coherence length of the femtosecond laser (typically tens of micrometers in our setup), holograms can be successfully recorded when the optical path lengths of the sample and reference arms (typically one meter) are carefully matched.

Second, inserting a Wollaston prism into the reference arm enables simultaneous holographic recording of two orthogonal polarization components. The corresponding polarization-multiplexed holograms can be separated in the spatial-frequency domain, where they produce two distinct pairs of lobes.

Figure 1 illustrates the proposed polarization-multiplexed SHG holographic setup: (a) the optical configuration, (b) the two SHG reference beams interfering with the sample beam, (c) the corresponding pairs of lobes in the spatial-frequency domain, and (d) (e) an example of the reconstructed 3D spatial distribution of collagen in a rat-tail tendon, acquired simultaneously for two orthogonal polarization components in a single camera exposure.

Beyond label-free 3D imaging of nonlinear proteins, this project aims to investigate the nonlinear optical response of nano-antennas made of metallic (typically gold), dielectric, or hybrid materials. The intrinsically weak SHG signal emitted by these nanostructures calls for advanced demodulation strategies to improve the signal-to-noise ratio of recorded holograms. This is complemented by exploiting the local-field

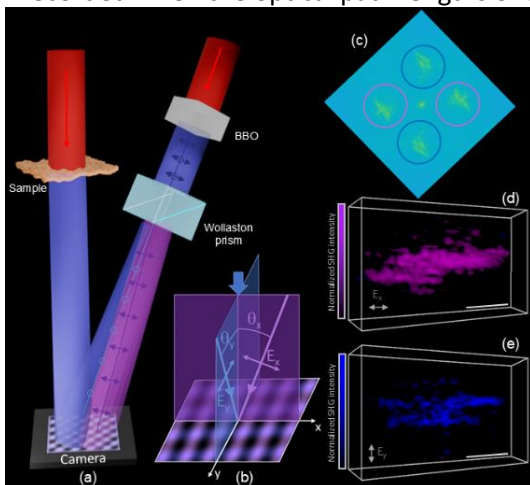


Figure 1: Polarization-multiplexed SHG holography illustrated for the 3D imaging of collagen with different orientations (linked to the polarization of the SHG signal) in a rat-tail tendon.

enhancement provided by plasmonic and Mie resonances of the nano-objects to boost SHG signals. Figure 2a shows the reconstructed SHG radiation pattern of an array of asymmetric gold bowtie nano-antennas, whose geometry is shown in Figure 2b. We observe a complex interference pattern known as a Talbot pattern. We aim to investigate the intrinsic SHG response of individual nano-antennas by characterizing both their radiation patterns and polarimetric responses. Ultimately, we aim to measure the full Stokes vector in 3D to characterize the polarization of the SHG emitted by the samples.

The internship/doctoral thesis will involve experimental development and characterization of the holographic setup, hologram acquisition and processing, and 3D reconstruction of SHG-emitting samples. Depending on the student's interests and progress, SHG polarization-resolved holographic imaging will be applied to both nanostructured and biological samples.

[1] Rahbany N., Izeddin I., Krachmalnicoff V., Carminati R., Tessier G., De Wilde Y., « One-Shot Measurement of the Three-Dimensional Electromagnetic Field Scattered by a Subwavelength Aperture Tip Coupled to the Environment », *ACS Photonics*, 5(4), 1539–1545 (2018). <https://doi.org/10.1021/acsp Photonics.7b01611>

[2] Goldmann S., Fondanèche M., Krachmalnicoff V., Chassot J.-M., Grésillon S., Lei D., Tessier G., De Wilde Y., « Second-harmonic generation holography with polarization multiplexing for label-free collagen characterization and imaging », *arXiv:2603.07798* (2026). <https://doi.org/10.48550/arXiv.2603.07798>

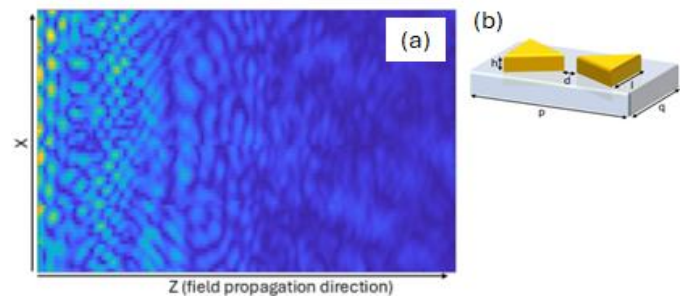


Figure 2: (a) Holographic 3D reconstruction showing in 3D the interference “Talbot” pattern of the SHG field as it propagates in free space from five asymmetric gold bowtie nano-antennas placed at $z=0$ and separated by 500 nm along the x axis. (b) Sketch of a single gold bowtie nano-antenna.