

LIGHTinPARIS		Marie Skłodowska-Curie Actions Second call for COFUND PhD fellowships
Employer	ONERA (French aerospace laboratory)*	
Doctoral School	EDOM (Waves and Matter)	
Selection Domain	ONERA (Waves and Matter)	
Supervision		
Thesis Director	Guillaume DRUART	
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Group / Team (website)	DOTA/ERIO	
French Lab Co-supervisor	Matthieu LANCY (ICMMO – France)	
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3i Institution - Country	ONERA – France	
* The requirements for obtaining access authorisation to the DOTA laboratory are very strict as ONERA (the employer) is a research centre under the supervision of the French Ministry of the Armed Forces.		
PHD THESIS PROJECT		
SCALING - Study of Complex And Laser-structured INDEX Gradient optics		
Summary / Abstract		
The objective of the thesis is to study the potential of complex GRIN optics (CGRIN) that can be produced by structuring matter with a femtosecond laser to address SWAP issues. This work will require the doctoral student to address the challenges of design, manufacturing, and metrology for CGRIN optics. Principal 3i dimension: intersectoral. Additional 3i dimension: interdisciplinary Keywords • GRIN • Lasers • optical design • Photochemistry • Imaging (biomedical imaging and microscopy, super-resolution, image sensors, lensless imaging, SNOM, ...) • Materials (inorganic, semiconductor, organic, liquid crystal, photochromics)		

SCALING - Study of Complex And Laser-structured INDEX Gradient optics

Key Objectives

Implementation of an index gradient model obtained by femtosecond laser in optical design codes.

Evaluation of the s-SNOM/nano-FTIR experimental method to control the quality of laser structuring and validate material structuring processes.

Manufacture of complex GRIN obtained by laser structuring

Project

Context and state-of-the-art of Scientific Research project

The field of imaging has undergone a revolution, initially in the visible spectrum, thanks to the reduction in pixel size, which has made it possible to effectively address the SWAP-C (size, weight, power, and cost) issue. This revolution has led to the widespread use of imaging in society with the emergence of new applications. The field of infrared imaging is also following this same trend. The main challenge now lies in the optical component, which is governed by its first-order characteristics (focal length, aperture) and by the physics of diffraction, which limits the optical resolution of the system. With smaller pixels, the optics must be more open in order to reduce the diffraction spot. This significant constraint means that simply adapting an old optical system is not possible, and new strategies must be devised to continue to address the SWAP-C issue. An initial strategy consisted of making optical surfaces more complex (aspherical, freeform) in order to increase the number of degrees of freedom without increasing the number of surfaces in the optical system. The second strategy consists of drawing inspiration from nature by using gradient index optics (known as GRIN lenses), i.e., optics whose index varies across their volume. As GRINs are more complex to produce than surface etching and polishing, the GRIN solution has so far been neglected in favor of complex surfaces. The recent emergence of new technologies for manufacturing GRIN optics (3D printing, laser structuring, stacking of polymer nanolayers, etc.) has brought GRIN optics back to the forefront. These technologies make it possible to consider complex GRINs (freeform, discontinuous, etc.). Furthermore, the combination of complex surfaces with complex GRINs (CGRINs) is entirely feasible for creating very open SWAP systems that are compatible with very small pixels. However, as with any emerging field, there are many challenges to be overcome, such as the optimization of systems with multiple degrees of freedom, their manufacture, and their metrology.

A Dutch thesis published in 2025 discusses the value of GRINs for SWAP-C issues. Several Dutch universities are participating in the FOCUS (Future Optical Components for Ultimate Dispersion Control Strategies) program, which focuses on freeform GRINs (FGRINs) obtained by 3D printing from nanoparticles-doped polymers (concept developed by American startup Nanovox following a DARPA project). The program plans to launch 12 theses in the field of FGRIN starting in 2026. These theses will address issues of design, materials, manufacturing, and metrology.

Description

The objective of the thesis is to study the potential of complex GRIN optics (CGRIN) that can be produced by structuring matter with a femtosecond laser to address SWAP issues. This work will require the doctoral student to address the challenges of design, manufacturing, and metrology for CGRIN optics.

ONERA is working with the ICMMO (Institut de Chimie moléculaire et des matériaux d'Orsay, Université Paris-Saclay) on theses and projects addressing the issue of structuring optical functions in matter using a

femtosecond laser. The ICMMO has a femtosecond laser capable of structuring a slab throughout its thickness to create controlled index variations that enable index gradients to be implemented. The first index gradient lenses and index gradient Fresnel lenses have been produced in parallel-sided slabs. Tables linking laser parameters to induced phase variations for commercial heavy oxide glasses or chalcogenide glasses have been established. Corning 9754 glass is of particular interest to us because it has very good mechanical properties, a transparency window from the visible to the MWIR, and allows significant index variations to be obtained by laser structuring. The thesis could be developed along the following lines:

- Implementation of an index gradient model obtained by femtosecond laser in optical design codes. In particular, this will involve studying the chromatic variation according to the wavelength of index gradients obtained by laser structuring using a Mueller IR ellipsometer (at the Soleil synchrotron) and implementing the index and absorption variation model as a function of wavelength in the commercial software ANSYS ZEMAX OPTICSTUDIO. Chromatic aberration correction with a laser-structured radial GRIN will be considered if the GRIN abbe number exhibits interesting properties.
- Evaluation of the usefulness of a measurement bench to control the quality of laser structuring and validate material structuring processes. The s-SNOM/nano-FTIR experimental method can be used to obtain nano-chemical maps of a material. This involves measuring the amplitude and phase of the field scattered at the tip to obtain local access to the dielectric function with a lateral resolution of approximately 10–50 nm. The homogeneity of the structures can then be probed. The origin of changes in index and phase can also be observed and exploited to improve the process of structuring matter using a femtosecond laser.
- Manufacture of optical components obtained by laser structuring. This will involve establishing charts of the variation in index/phase measured in the visible and SWIR ranges as a function of the laser properties and the depth of structuring. Several optical functions obtained by stacking layers will be considered (GRIN freeform, high-order Fresnel lens). The impact of parasitic microstructures on image quality will be evaluated. This study addresses the issue of designing optical systems with multiple degrees of freedom. The implementation of GRIN optics in the differentiable ray tracing software developed at ONERA (called FORMIDABLE) will be considered. Differentiability allows for more efficient optimization than commercial optical design software for systems with many degrees of freedom.

Throughout these different areas of study, the doctoral student will be required to design and produce optical components with various functionalities (imaging, phase shifting, etc.). These components will be integrated into optical systems whose imaging performance will be evaluated experimentally. The gradient index profiles created by the doctoral student will be analyzed either by solving the intensity transport equation at ICMMO and/or by measuring the wavefront with a Phasics-type analyzer at ONERA.

This thesis is an opportunity to develop a wide range of skills (modeling, optical optimization, implementation of a laser bench, metrology, characterization of optical performance, etc.). The expected results are:

- Publications in peer-reviewed journals
- Oral presentations at international conferences
- Numerical modeling
- Experimental achievements, including at least one proof of concept.

Bibliography

- M. Lancry et al., 'Ultrafast nanoporous silica formation driven by femtosecond laser irradiation,' Laser Photonics Rev. 7, No. 6, 953–962 (2013)
- Desmarchelier, R. et al., 'Achromatic polarization rotator imprinted by ultrafast laser nanostructuring in glass', Applied Physics Letters 107, 181111 (2015)
- M. Beresna et al., 'Broadband anisotropy of femtosecond laser induced nanogratings in fused silica,' Applied Physics Letters 103, 131903 (2013)
- R. Dylla-Spears, T. D. Yee, D. T. Nguyen, N. A. Dudukovic, J. M. Ortega, M. A. Johnson, O. D. Herrera, F. J. Ryerson, and L. L. Wong, '3D printed gradient index glass optics,' Science Advances 6, 7 (2020)
- T. Yang, N. Takaki, J. Bentley, G. Schmidt, and D. T. Moore, 'Efficient representation of freeform gradient-index profiles for non-rotationally symmetric optical design,' Optics Express 28, 14788 (2020)
- N. S. Kochan, G. R. Schmidt, and D. T. Moore, 'Freeform gradient index progressive addition lens raytrace performance evaluation,' Applied Optics 61, A28 (2022)
- Sun X, Zhou F, Duan L., 'An Annular Fresnel Zone Plate without Central Spots Fabricated by Femtosecond Laser Direct Writing', Micromachines. 2022; 13(8):1285.
- Boyd, A. M. (2025). Optical Design of Generalised Gradient-Index Lenses: for the optimisation of size, mass and cost-critical optical systems. [Dissertation (TU Delft), Delft University of Technology].
- Lippman, D. H., Kochan, N. S., Yang, T., Schmidt, G. R., Bentley, J. L., & Moore, D. T. (2021). Freeform gradient-index media: a new frontier in freeform optics. Optics Express, 29(22), 36997-37012.
- P. Deluillier, G. Druart, F. De La Barrière, L. Calvez, and M. Lancry, "Femtosecond Laser Direct Writing of Gradient Index Fresnel Lens in GeS₂-Based Chalcogenide Glass for Imaging Applications," Appl. Sci. 2022, 12(9), 4490;

Facilities and quality of research environment available for the researcher

The doctoral student will have the opportunity to design and produce optical components with various functionalities (imaging, phase shifting, etc.). These components will be integrated into optical systems whose imaging performance will be evaluated experimentally. The gradient index profiles created by the doctoral student will be analyzed either by solving the intensity transport equation at ICMMO and/or by measuring the wavefront with a Phasics-type analyzer at ONERA.

This thesis is an opportunity to develop a wide range of skills (modeling, optical optimization, implementation of a laser bench, metrology, characterization of optical performance, etc.). The doctoral student will benefit from the skills and experimental resources available in the DOTA and ICMMO laboratories, as well as the application framework of several collaborative projects.

3i Dimensions - intersectoral, interdisciplinary

Description and expected outcomes

The thesis primarily meets LighInParis' interdisciplinary criteria. Indeed, the PhD student will have to develop skills in both optical instrumentation (typical optical design, optimization strategy, aberration theory, figure-of-merit analysis, modeling etc.) and laser-matter interaction (nano/micro-structuration by means of various laser irradiations, implementation of a laser bench, metrology, study of different materials etc). In addition, the progress of the thesis work will open up opportunities in the inter-sectoral aspect, as the PhD student will work at ONERA, will be able to benefit from the experience of industrial partners via the FO-RS association and from . Last but not least, the open-ended work of this thesis will enable FORMIDABLE (under ESCL license) to evolve, from which the European community will benefit, adding an international aspect.

Approximate timeline of internships / external stays corresponding to the 3i dimension

- **Year 1 (October 2026 – September 2027)**

50% ONERA / 50% ICMMO

- **Year 2 (October 2027 – September 2028)**

50% ONERA / 50% ICMMO

- **Year 3 (October 2028 – September 2029)**

50% ONERA / 50% ICMMO

Profile of PhD fellow

PhD studies and research work require curiosity, creativity, rigour, teamwork, and organisational skills. A minimum B2 level of English is mandatory. The below criteria are specific to the thesis project.

pre-requisite	Theoretical knowledge in Optics
pre-requisite	Experimental experience working with Lasers
pre-requisite	Experimental experience in Imaging
advantageous	Academic background in Materials or Photochemistry
advantageous	Academic background in Applied Mathematics

Ethics issues in the project as per Horizon Europe Ethics Self-assessment

Section 1. Human embryonic stem cells (hESCs) and human embryos (hEs)			No
Section 2. Humans	No	Section 3. Human cells and tissues	No
Section 4. Personal data	No	Section 5. Animals	No
Section 6. Third Countries	No	Section 7. Environment, health and safety	Yes
Section 8. Artificial Intelligence	Yes	Section 9. Other ethics issues	No
Section 10. Crosscutting issue: potential misuse of results			No

7. Environment, health and safety

All French labs are required to have health and safety procedures in place, which takes into account the use of high-energy light sources such as lasers of class 3 and above, and the use of hazardous / toxic chemical and biological products. The institution and the laboratory comply with the highest safety requirements and PhD fellows have mandatory health and safety training, with additional training if required.

8. Artificial intelligence

The use of machine learning and artificial intelligence is used to fit data and analyse results. This is typically used to improve fits and complex models with multiple parameters. The data in question is related to physical experiments and is not human data.

Artificial Intelligence is not developed during this project and is thus not impacted by the AI Act.