UNIVERSITÉ MARIE & LOUIS PASTEUR

femto-st SCIENCES & TECHNOLOGIES

école doctorale **sciences physiques** pour l'**ingénieur** et **microtechniques** SPIM

Titre de la thèse/Thesis title : Light-Controlled Nonlocal Mechanical Metamaterials: Bridging Optomechanics and Nonlocal Elasticity

Laboratoire d'accueil / Host Laboratory : FEMTO-ST

Spécialité du doctorat préparé/Speciality : Mechanics

Mots-clefs / Keywords : Metamaterials, waves, optomechanics, elasticity

Descriptif détaillé de la thèse / Job description

Introduction and Scientific Context: Mechanical metamaterials [1-8] have revolutionized how we design materials, demonstrating that **geometry can dominate over composition** to produce exotic properties such as negative Poisson's ratio, tunable bandgaps, and wave manipulation. However, most existing metamaterials are still governed by **local continuum mechanics and have limited dynamic properties (particularly low losses at low frequencies)** , where interactions are restricted to neighboring elements and effective properties are fixed after fabrication .

Recent advances in optomechanics and nanoscale physics suggest a paradigm shift: **mechanical responses can be actively controlled using external fields**, especially optical forces. In parallel, emerging theoretical developments show that **nonlocal elasticity**, where interactions extend over finite distances, is required to describe such systems accurately. The combination of these two directions opens a fundamentally new research avenue: **field-mediated, nonlocal, and dynamically programmable metamaterials**. This PhD project aims to bridge **optomechanical control** and **nonlocal elasticity theory** to develop a new class of materials in which **light not only actuates mechanical behavior but also induces and controls nonlocal interactions across the structure**.

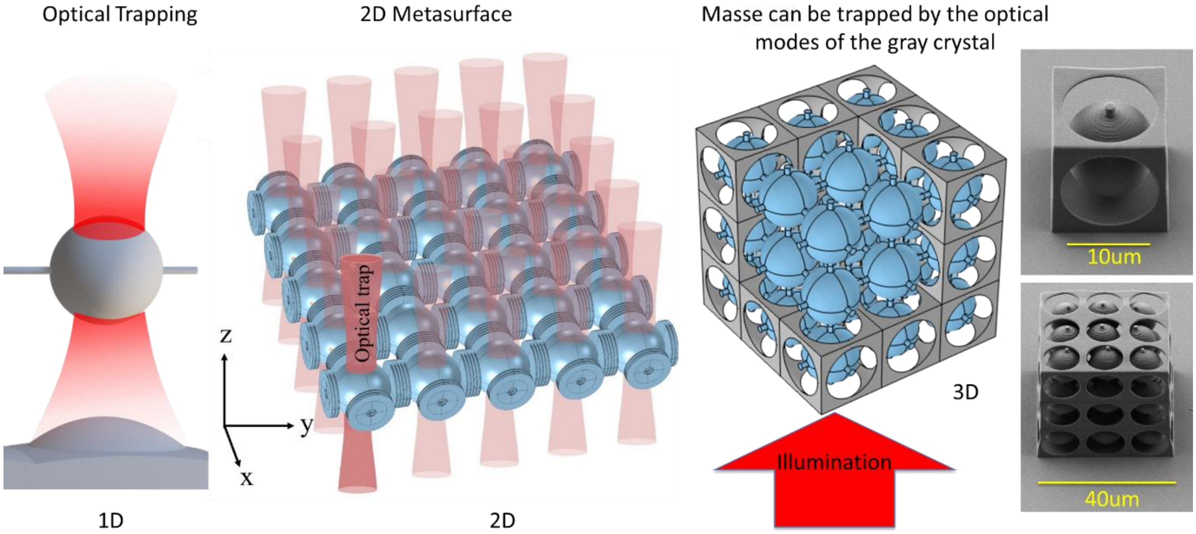

Figure 1. **Optomechanical metamaterial with light-induced trapping and lattice-scale control.** Schematic illustration of an optomechanical unit cell (left) where a dielectric micro-element is confined by an optical trap generated by a focused laser beam, producing controllable gradient and radiation-pressure forces. Extension to a three-dimensional periodic lattice (center) shows an array of mechanically coupled resonators interacting with spatially distributed optical fields (red cones), enabling collective and reconfigurable mechanical behavior. The architecture supports field-induced tuning of stiffness and wave propagation through optically mediated interactions. Right: CAD rendering of the designed 3D unit cell and corresponding fabricated microstructures obtained via high-resolution two-photon lithography, demonstrating precise realization at the microscale (scale bars: 10 µm and 40 µm).

Research Objectives: The central objective of this PhD is to establish a **unified framework for light-controlled nonlocal mechanical metamaterials**, integrating experimental optomechanical design with advanced theoretical modeling.

Specifically, the project will:

- Develop 3D **optomechanical metamaterial architectures** where light acts as a tunable mechanical interaction (optical springs, radiation pressure, gradient forces).
- Formulate a **nonlocal elasticity framework** capable of incorporating optical forces as long-range couplings.
- Demonstrate **light-induced nonlocal behavior**, such as spatially extended stiffness modulation and dispersion engineering.
- Validate theoretical predictions through **numerical simulations and experimental prototypes**.

This research directly addresses the limitation of classical continuum models, which cannot capture **field-mediated, long-range interactions**.

In more details:

Optomechanical Metamaterials Optomechanical systems exploit the interaction between light and mechanical motion. Optical forces—such as **radiation pressure and gradient forces**—can act as tunable, non-contact interactions capable of modifying stiffness and wave propagation in real time .

As described in the document (see *Figure 1*), a chain of mechanical elements can be coupled via **optical "springs"**, allowing dynamic control of band structures and elastic properties. Extending this concept to 3D lattices enables: (i) Light-controlled stiffness modulation, (ii) Tunable phononic bandgaps, (iii) Reconfigurable waveguiding

These systems offer **ultrafast and spatially precise control**, which is not achievable with traditional actuation methods.

Theory of Nonlocal Elasticity Classical elasticity assumes that stress depends only on local strain. However, this assumption breaks down when **long-range forces (e.g., optical fields)** are present.

We will introduces a **nonlocal continuum framework**, where stress is expressed as an integral over space: $\sigma_{ij}(x) = \int C_{ijkl}(x,x')\,\varepsilon_{kl}(x')\,dx'$

This formulation allows capturing: (i) **Spatially extended interactions, (ii) Non-monotonic dispersion (roton-like behavior), (iii) Field-dependent mechanical properties**

The framework also incorporates **fractional operators and multiphysics couplings**, enabling a rigorous description of metamaterials beyond classical homogenization.

Research Methodology

The PhD will follow a **combined theoretical, numerical, and experimental approach**:

Theoretical Development: (i) Formulate nonlocal elasticity models incorporating **optical force terms** derived from Maxwell stress tensor. (**ii**) Introduce **nonlocal kernels or fractional operators** to describe light-induced interactions. (**iii**) Extend elastodynamic equations to include optomechanical coupling.

Numerical Modeling: (i) Implement models using **finite element methods (FEM)** and spectral solvers. (ii) Simulate dispersion relations and identify **nonlocal signatures induced by light**. (iii) Explore regimes where optical forces dominate over classical elastic interactions.

Optomechanical Design: (i) Design **photonic-mechanical unit cells** (e.g., dielectric resonators embedded in lattices). (ii) Optimize geometries for strong **light–matter coupling**. (iii) Investigate 1D and 3D lattice configurations.

Experimental Validation (optional/depending on project scope): (i) Fabricate structures using **two-photon lithography**. (ii) Characterize mechanical response under controlled illumination. (iii) Measure **light-induced bandgap shifts and stiffness modulation**.

5. Expected Results and Contributions

This PhD is expected to deliver both **fundamental and applied breakthroughs**:

- First demonstration of **optically induced nonlocal elasticity** in metamaterials

- A unified theory linking **optomechanics and nonlocal continuum mechanics**
- New understanding of **field-mediated dispersion and wave propagation**
- Development of **light-programmable materials**
- Applications in Wave control and vibration isolation for MEMS/NEMS devices

Bibliography

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[8] P. Jiao, Q. Zhang, D. M. Kochmann. "Mechanical metamaterials and beyond." *Nature Communications* **14** (2023): 41679.

Applicant profile

The ideal candidate should have a strong background in physics, mechanics, or engineering, with solid knowledge of continuum mechanics, wave propagation, or photonics, and an interest in interdisciplinary research at the interface of mechanics and optics. Experience in numerical modeling (e.g., FEM) and/or micro–nano fabrication or experimental techniques is highly desirable, along with strong analytical skills and motivation to work on cutting-edge metamaterials.

Preferred selection criteria:
- Physics or engineering school in mechanics or optics
- with a research experience during master's intership
- with programming skills in FEM and Matlab

Personal characteristics:
- Autonomous, B2 in English

Financement : MESRI Etablissement

Dossier à envoyer pour le **15 mai 2026**
Début du contrat : 1er Octobre 2026
Salaire mensuel brut : 2300€

Thesis Supervisor
Muamer Kadic / e-mail : muamer.kadic@univ-fcomte.fr

Encadrement de la thèse : **Gwenn Ulliac (co-encadrant)**

Applicants are invited to submit their application to the PhD supervisors.
Application must contain the following documents:
- CV
- Cover letter
- At least 1 reference letter
- A short description of the thesis topic understanding from the candidate (2 pages)