1. **PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan)**

Project title: Nanophotonic architectures inspired by 2D materials

1.1. Project goals

The primary goal of this project is to explore and exploit the potential of nanophotonic architectures inspired by the geometrical and physical properties of two-dimensional (2D) materials. By engineering photonic lattices where individual components act as optical analogues of atoms, the project aims to emulate and extend electron-like phenomena in a highly controllable optical environment. Key objectives include:

- Understanding the analogies between electronic phenomena in 2D materials and their optical counterparts in engineered photonic architectures. Adjusting the methodology known from condensed matter physics to the realm of photonics.

- Investigating light-based analogues of quantum phenomena, e.g., topological protection, defect-localized modes, or photonic flat bands.

- Pushing the boundaries of what is physically possible with traditional 2D materials by exploiting the design flexibility of artificial photonic platforms, e.g., non-Hermitian physics, topological lasing, and spin-momentum locking.

1.2. Outline

Artificial photonic architectures are structured arrangements of waveguides, microcavities, or nanoparticles that mimic the lattice patterns of low-dimensional materials, like 1D atomic arrays or 2D nanoflakes of graphene. These systems allow light to simulate quantum phenomena usually associated with electrons, providing a powerful testbed for studying fundamental physics in a simplified and tunable setting.

Unlike atomic crystals occurring in nature, these engineered systems permit local modifications and non-Hermitian features, leading to a broad range of emergent behaviours not accessible in conventional condensed matter systems. This project involves both theoretical modeling and computational simulations to understand and design such architectures.

We will use existing codebases and simulation tools to analyze light-matter interactions in these platforms, adapting techniques from both photonics and quantum physics. The project focuses on developing predictive models and identifying regimes where novel photonic phenomena can arise, aiming for both conceptual advances and potential technological impact.

1.3. Workplan

The work plan is structured into the following main tasks:

Task 1: Theoretical Framework Development

- Adaptation of the tight-binding approach to photonic systems.
- Adaptation of the quantum master equation framework to capture the dynamics of light in photonic architectures.

Task 2: Computational Modeling

- Modification of existing Python-based codes in the group to incorporate nanophotonic properties and simulate optical responses of engineered structures.
- Validation of simulation results against known quantum and classical limits and benchmark cases.

Task 3: Exploration of Novel Phenomena

- Investigation of conditions for observing effects such as non-Hermitian physics, topological protection, or spin-momentum locking in photonic lattices.
- Mapping out parameter regimes where artificial lattices outperform their electronic analogues in tunability and functionality.

Task 4: Integration and Dissemination

- Synthesizing the results into a coherent framework summarized in the thesis.
- Preparation of findings for publication in the form of articles and dissertation; presentation of results at conferences.

1.4. Literature *(max. 7 listed, as a suggestion for a PhD candidate preliminary study)*

1. Y. Chen et al., Phys. Rev. A **104**, 023501 (2021)
2. D. N. Christodoulides et al., Nature **424** (6950), 817 (2003)
3. D. Neshev et al., Opt. Lett., **29**(5), **486** (2004)
4. L. Feng et al., Nat. Photon. **11**, 752 (2017)
5. S. Stützer et al., Nature **560**, 7719, 461 (2018)
6. M.Kosik et al., Nanophotonics **11**(14), 3281, (2022)
7. Toolbox documentation: https://granadlauncher.github.io/granad/

1.5. Required initial knowledge and skills of the PhD candidate

Basic experience in at least one of the following disciplines:

- quantum optics,
- quantum solid-state theory,
- atomic/molecular physics,
- classical electrodynamics.

Experience in numerical simulations or programming.
Proficiency in oral and written communication in English.

1.6. Expected development of the PhD candidate's knowledge and skills

Over the course of the project, the PhD candidate will gain interdisciplinary expertise at the interface of photonics, quantum physics, and computational modeling. They will:

- **Develop an understanding of light-matter interactions in structured photonic systems**, including concepts from quantum optics, non-Hermitian physics, and topological photonics.
- **Acquire proficiency in theoretical modeling techniques**, such as the tight-binding approximation for photonic lattices, quantum master equations, and effective Hamiltonian methods.
- **Strengthen computational and simulation skills** through hands-on experience with a numerical Python-based toolbox.
- **Improve scientific communication skills**, including writing high-quality research articles, presenting at international conferences, and engaging with interdisciplinary collaborators.
- **Gain project management and research autonomy**, progressively taking ownership of scientific planning, goal-setting, and dissemination of results.

By the end of the PhD, the candidate will be well-equipped for a research career in academia or industry, with a strong foundation in both fundamental physics and advanced simulation techniques relevant to quantum technologies and photonics.
