Quantum Photonic Integrated Design Center (QuPIDC)
EFRC Director: Libai Huang
Lead Institution: Purdue University
Class: 2024 – 2028

***Mission Statement**: to discover, design, and realize robust many-body entangled photon and matter states through multi-scale co-designing strategies in heterogeneous solid-state photonic systems.*

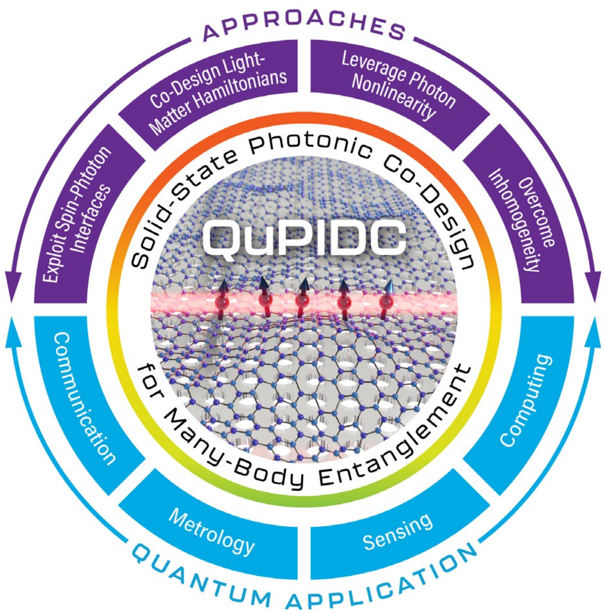

Figure 1. **QuPIDC** targets the realization of resilient many-body entangled states of photons and matter. The illustration depicts the entanglement of spins from multiple emitters in a h-BN layer with a disordered energy landscape and coupled to a photonic crystal.

Photonic platforms based on solid-state materials present a promising path toward the scalable generation of complex quantum states of light, which are essential for the development of quantum networks, entanglement-enhanced metrology, and optical quantum computation. The key enabler of these technologies is the efficient and reliable generation of quantum light. Solid-state quantum emitters—including defects, quantum dots, molecules, and two-dimensional (2D) materials—have demonstrated significant potential for generating quantum light, while advances in nanophotonic structures have made it possible to manipulate light at the chip level.

However, despite the progress, significant scientific challenges remain, particularly regarding scalability. Inhomogeneities and dephasing, which are inherent to solid-state systems, have limited the generation of quantum light to small photon numbers. Addressing noise channels, such as decoherence and inhomogeneity, is essential for advancing quantum photonic systems. Moreover, new strategies are required to generate and characterize robust, many-photon entangled states in the presence of imperfections.

The **Quantum Photonic Integrated Design Center (QuPIDC)** aims to systematically address these challenges by leveraging the complexity and imperfections of solid-state materials to discover, design, and realize robust many-body entangled photon and matter states. This will be achieved through a multi-scale co-design strategy that integrates solid-state quantum emitters with advanced nanophotonic structures. The QuPIDC team is uniquely equipped for this mission, with expertise spanning solid-state quantum emitters, nanophotonics, materials growth, quantum optics, ultrafast spectroscopy, and quantum many-body dynamics.

QuPIDC's Goals

Over the next four years, QuPIDC will pursue three primary goals:

1. **Co-design Quantum Emitters and Nanophotonic Structures**: The center will integrate quantum emitters with nanophotonic structures to reduce decoherence, increase photon collection

efficiency, and enable control over spin and polarization. This integration will also enhance nonlinear interactions crucial for generating quantum light.

2. **Prepare Entangled Photon and Emitter States in Inhomogeneous Systems**: Using Hamiltonian engineering and quantum control strategies, QuPIDC will generate entangled states of photons and emitters within complex, inhomogeneous systems. This approach will allow the creation of robust quantum states despite intrinsic material imperfections.
3. **Develop New Theoretical and Experimental Tools**: QuPIDC will create innovative theoretical frameworks and experimental techniques to identify, generate, and characterize complex quantum states of light and matter. These tools will be essential for realizing many-photon quantum states that are resilient to noise and loss.

Key Research Areas

To achieve these goals, QuPIDC will focus on several key areas of research, which include:

- **Nanophotonic Structure Design**: The center will design dielectric and plasmonic nanophotonic structures that enhance the optical and spin coherence of quantum emitters, including h-BN, transition metal dichalcogenides (TMDs), Cu_2O, GaAs quantum dots, organic molecules, and color centers in SiC, SiN, and diamond.
- **Co-designing Light-Matter Interactions**: QuPIDC will co-design photon-emitter interfaces to maximize nonlinear photon interactions, critical for increasing photon entanglement. These enhanced light-matter interactions will enable the realization of highly entangled photon states, including cluster states, superradiance, Fock states, and squeezed light.
- **Quantum Control and Characterization**: Theoretical and experimental techniques will be developed to control and characterize entangled photon states and multi-emitter systems.

Alignment with BES Research Priorities

QuPIDC's research strategies align with the **Priority Research Directions (PRDs)** and **Priority Research Opportunities (PROs)** outlined in the Basic Energy Sciences (BES) workshop and roundtable reports. Specifically, QuPIDC's emphasis on the co-design of quantum emitters and nanophotonic structures directly supports the transformative materials paradigm for quantum information science. The center's development of a comprehensive suite of theoretical and simulation tools will address bottlenecks in experimental preparation and characterization of complex quantum states.

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