Campagne 2020 Contrats Doctoraux Instituts/Initiatives

Proposition de Projet de Recherche Doctoral (PRD)

Appel à projet CIQ - Centre d'information quantique 2020

Intitulé du Projet de Recherche Doctoral :
Multiplexed optical memories for quantum networks

Directeur de Thèse porteur du projet (titulaire d'une HDR) :

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Unité de Recherche :
Intitulé : Laboratoire Kastler Brossel
Code *(ex. UMR xxxx)* : UMR 8552

Ecole Doctorale de rattachement de l'équipe & d'inscription du doctorant : **ED564-Physique en IdF**

Doctorants actuellement encadrés par le directeur de thèse (préciser le nombre de doctorants, leur année de 1ere inscription et la quotité d'encadrement) : 4 (2017,2018,2018,2019)

Co-encadrant :

NOM : **DIAMANTI** Prénom : **Eleni**
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Unité de Recherche :
Intitulé : LIP6
Code *(ex. UMR xxxx)* : UMR7606

Ecole Doctorale de rattachement : **ED130-EDITE**
Ou si ED non Alliance SU :

Doctorants actuellement encadrés par le co-directeur de thèse (préciser le nombre de doctorants, leur année de 1ere inscription et la quotité d'encadrement) : 5 (2017,50%; 2018,50%; 2018,50%; 2018; 2019,50%)

Cotutelle internationale : ☒ Non ☐ Oui, précisez Pays et Université :

Description du projet de recherche doctoral *(en français ou en anglais)*

3 pages maximum – interligne simple – Ce texte sera diffusé en ligne

Détailler le contexte, l'objectif scientifique, la justification de l'approche scientifique ainsi que l'adéquation à l'initiative/l'Institut.
Le cas échéant, préciser le rôle de chaque encadrant ainsi que les compétences scientifiques apportées. Indiquer les publications/productions des encadrants en lien avec le projet.
Préciser le profil d'étudiant(e) recherché.

Multiplexed optical memories for quantum networks

1/ Scientific Objectives

In the broad context of quantum communications, one stream of research aims at eventually creating a so-called Quantum Internet. Among other applications, ranging from extending the baseline of telescopes to clock synchronization and sensor networks, the creation of a Quantum Internet would enable long-distance unconditionally-secured information transfer. Central to this endeavor is the concept of **quantum repeater**. It consists in dividing a communication channel between two end nodes into various shorter segments over which entanglement can be faithfully distributed. Adjacent segments are then connected by entanglement swapping operations. To be scalable, this approach requires **quantum memories** (QMs), which enable quantum states to be stored at each intermediate node.

A central direction for the field is to improve the achievable rates for useful protocols, such as creating entanglement between light and quantum memories. In this context, a critical challenge is to **go beyond single-mode QMs**. This can be addressed by multiplexing to create **multimode quantum memories**, which is equivalent to running a **protocol for each mode in parallel**. This method not only allows more information to be stored on a single device but, importantly, can also be used to increase the success rate per attempt for entanglement generation. Several multiplexing methods can be explored, such as multiplexing in time, frequency, and space.

In this context, the spatial degree of freedom is a promising candidate and will be explored in this project. Relying on the cold-atom quantum memory setup available at LKB, we will target the realization of rate-enhanced light-matter entanglement generation between two separated labs on the Sorbonne Université P. et M. Curie campus, LKB and LIP6, via Space Division Multiplexing (SDM).

2/ State-of-the-art and Methodology

Significant advances have been made for quantum networks in the last decade, including very first rudimentary capabilities for quantum repeater architectures. However, most of these seminal demonstrations were plagued with limited efficiency and scalability. In the more recent years, optical memories have been largely improved due to the rapid progress in implementing elongated ensemble of cold neutral atoms with ultra-high optical depths, which a strong prerequisite for large efficiency. Using **a large cold atomic ensemble based on an elongated magneto-optical trap (3-cm long)**, in 2018, the LKB team demonstrated qubit storage with an overall efficiency close to 70%, a value that doubled the usual performances at that time. This year, the **team pushed this value even higher and reached the 90% mark for entanglement storage**. This is the state-of-the-art in term of storage-and-retrieval efficiency for a quantum memory, regardless of the physical platform considered.

Based on this existing setup, the project will combine for the first time quantum memory and the concept of Space Division Multiplexing (SDM), which is a hot topic in the optical communication community. The work will be based on commercial **mode-selective multiplexer and demultiplex**er. Starting from 20 independent single-mode fibers, the SDM device can output up to 20 Hermite-Gaussian (HG) modes overlapped in a single beam, with cross talks below 20 dB. Reciprocally, the demultiplexer can separate the beam into its individual mode components which are coupled back to single-mode fibers. **The parallelization of quantum information storage** constitutes a timely research field for subsequent implementations as scalability is the main hurdle at present. This research takes the challenge to explore the spatial multiplexing paradigm. Other groups have also started this line of research, including the demonstration of three-dimensional OAM states entanglement and the generation of multiple photons using a generalized DLCZ protocol. However, these approaches are either limited in number of modes, or rely on wave-vector multiplexing (different angles of incidence), which limits the optical depth per mode and thereby the achievable efficiency.

After developing a photonic setup based on mutiplexer/demultiplexer, the thesis will focus on storing multiple modes into the memory and benchmarking the performances, in the classical and then in the single-photon regime. **A final step will be to demonstrate light-matter entanglement generation at an enhanced rate via SDM between the LKB lab where the memory is located and the LIP6 lab**

where characterization and subsequent use for remote state preparation will be realized. A typically 1km-fibre-bundle link will be deployed and stabilized between the two locations. The heralding rate will be compared with the non-multiplexed one and a factor >10 increase is targeted. This demonstration aims at validating the SDM approach in real-world environment for an increased quantum networking capacity.

3/ Synergies and Interactions in QICS

The present research activity will strengthen the already established collaboration between the LIP6 and LKB labs and will enable to take a first step **towards a 'quantum-connected' campus by demonstrating entanglement between the two remote labs**. Multiplexing is an instrumental step, as it was the case for classical telecommunications. The proposed work is part of this effort and takes an original approach based on SDM techniques. The project outcomes will eventually provide a **key component that is required for the envisioned mid-term project of a quantum communication infrastructure (QCI) in the Ile-de-France region** towards the first repeater segments for quantum information distribution on deployed fibers, developed under the responsibility of LIP6. More generally, this is part of the ambitious EuroQCI project, which aims at deploying such testbeds in several major cities in Europe for unlocking the full potential of quantum communication technologies. Beyond experimental implementations, efforts to develop the memory protocols we propose in this thesis project will provide benchmarks in terms of figures of merit (multimode character, efficiency lifetime, added noise) that are necessary to design and validate potential network architectures and future applications. The LIP6 team has an extended expertise on the design, analysis and implementation of quantum network protocols that can be used as blueprints for the future Quantum Internet. Such protocols allow demonstrating a provable quantum advantage for applications such as delegated and distributed quantum computing, and advanced quantum cryptographic functionalities relying on entanglement distribution and verification. The state-of-the-art quantum-memory based link that we propose to build as part of this thesis will provide a **crucial testbed for benchmarking protocols that belong to the so-called quantum memory stage of quantum networks**, hence placing our University in the forefront of advances in this field.

4/ Recent publications related to the research context:

LKB:

- M. Cao *et al.*, Efficient reversible entanglement transfer between light and quantum memories, under review (2020).
- P. Vernaz-Gris *et al.*, Highly-efficient quantum memory for polarization qubits in a spatially-multiplexed cold atomic ensemble, Nature Commun. 9, 363 (2018)
- V. Parigi *et al.*, Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory, Nature Commun. 6, 7706 (2015).

LIP6:

- Unnikrishnan *et al.*, Anonymity in practical quantum networks, Phys. Rev. Lett. 122, 240501 (2019).
- M. Bozzio *et al.*, Experimental investigation of practical unforgeable quantum money, npj Quantum Information 4, 5 (2018).
- W. McCutcheon *et al.*, Experimental verification of multipartite entanglement in quantum networks, Nature Commun. 7, 13251 (2016).

The dynamic and highly-motivated PhD candidate should have an initial training on experimental quantum photonics, light-matter interactions or quantum information technologies.