Semester 2: University of Porto

Contents

Plan of Studies

Compulsory

Code	Name	Contact hours	ECTS
FIS4047	Introduction to quantum information	42 TP	6
FIS4046	High Performance Computing in Quantum Matter	42 TP	6
FIS4044	Quantum Matter	42 TP	6
CC4011	Computational Complexity	42 TP	6
	Language Course		3

Options

Code	Name	Contact hours	ECTS
	Quantum field and Statistical Theory	42 TP	6
	Internship (*)	14 OT	6

(*) Intership projects are detailed below and soma take place at Iberian Nanotechnology laboratory in Braga (50 Km from Porto, with regular trains connections)

Introduction to quantum information

Code FIS4047

link: https://sigarra.up.pt/fcup/en/UCURR_GERAL.FICHA_UC_VIEW?pv_ocorrencia_id=509996

Teaching components (total hours in semester)

T	TP	PL	Total Contact hours	ECTS	Total hours of student work
	42		42	6	162

Lecturers

Ariel Ricardo Negrão da Silva Guerreiro (asguerre@fc.up.pt)

Goals

The main objectives of this curricular unit are:

- Development of a mind map of quantum information theory, its interconnection with other science disciplines and applications in quantum technologies; and
- Understanding the concepts, models and fundamental knowledge of this theory and acquiring skills in its operationalization and extension, leading to the progressive autonomy of students in understanding the specialized scientific literature and in the study of more advanced disciplines, promoting the ability to develop research and development activities in this area.

- From this derive several other objectives, namely:
  - To promote the connection of knowledge and principles of the Quantum Theory of Information with those of other areas of Science and Physics Engineering, its framing in an integrated view of Physics and Modern Sciences and their technological applications.;
  - To know the general structure of the quantum theory of information, of consubstantiation in physical systems, with particular emphasis on its fundamental principles and laws;
  - To operationalize the mathematical formulation and calculation methods in Quantum Information Theory;
  - To be able to establish a relationship between the conceptual and formal models of the theory of Quantum Information Theory and research work in the area, albeit at an elementary level.
  - Develop scientific intuition and critical thinking;
  - To provide the knowledge base and competences necessary for students to be able to continue their studies in more advanced areas of knowledge.

In addition to the technical and scientific aspects, this curricular unit should also contribute to increasing the culture of students in Physics, Engineering and Science.
In addition to these general objectives, it is intended that, for students to pass this curricular unit, they must meet the following minimum learning goals:

- to know the fundamentals, techniques and most relevant results of the Quantum Theory of Information;
- to be able to use the theoretical and formal technical tools of this discipline in problem solving and model building;
- to be able to identify the limitations and validity domains of the models;
- to be able to identify and understand the most relevant current applications and research topics in Quantum Information Theory.

Learning Outcomes and Skills

Development of a mind map of quantum information theory, its interconnection with other science disciplines and applications in quantum technologies; and

Understanding the concepts, models and fundamental knowledge of this theory and acquiring skills in its operationalization and extension, leading to the progressive autonomy of students in understanding the specialized scientific literature and in the study of more advanced disciplines, promoting the ability to develop research and development activities in this area.

Subject Matter

1. Introduction to Quiskit.
2. Introduction to information theory.
Historical view. Statistical description of the information. Entropy and information measurements. Theory of estimation and inference. Fisher information and Cramer-Rao limit.
3. Mathematical structure of quantum theory.
Elementary quantum theory. Multiparty systems and quantum sets (density operator, separability, nonlocality, entanglement and heat). Quantum dynamics and open systems (quantum operations, noise and decoherence). Measure and indeterminacy (projection and not demolition measures, P.O.V.M. and Q.S.T.)
4. Information in quantum registers.
Theorems “no-go”, “no-cloning”, “no-broadcast” and “no-deleting”. Entanglement as a resource (Bell states and inequalities, entanglement and information measures).
5. Second-generation quantum technologies.
Communications, computing, simulation and quantum sensors (teleportation, QKD, dense coding, quantum algorithms, error correction, quantum sensing protocol).

Main Bibliography

Mandel L. (Leonard) 340; Coherence and quantum optics. ISBN: 0-306-307

Complementary Bibliography

...

Teaching Methods and Learning Activities

The curricular unit Introduction to Quantum Information is an optional curricular unit that is integrated in the 1st or 2nd year of the Master in Physics and Master Quarmen course. Therefore, their attendance presupposes knowledge of Linear Algebra and General Mathematics, as well as basic knowledge of Quantum Mechanics, Electromagnetism and Electrodynamics, which are subjects covered at the level of a first cycle of studies in Engineering Physics, Physics, Mathematics, and Computer Science.

Key words

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Description of assessment

Pratical project: 50%
Final exam 50%
A student-centered methodology is chosen, in which the chapters of the recommended bibliography for prior study are previously identified, accompanied by activities that aim to focus the student on the relevant concepts, models and knowledge, leading to their operationalization and the development of skills previously explained. Contact hours consist of classes that combine exposition, discussion and application of the contents prepared in the previous study. These are supplemented with problems and individual solving exercises that cover the topics and methods studied, having varying levels of difficulty. Mostly, its resolution resorts to methodologies based on the Quiskit platform, introduced in the first classes and whose usage skills are developed throughout the school period, along with the remaining contents.

The assessment consists of:
1. Solving proposed problems (50%)

2. Final exam (50%)

The final exam is carried out at home with consultation and over a period of 24 hours and seeks to assess students' ability to combine the knowledge of the various chapters, carrying out some research on the topic and being able to use simulation or numerical calculation tools, in order to build a small model that describes a situation or solves a problem or problems.

Observations

Any situation not foreseen in this discipline regulation must be communicated to the teacher during the first two weeks of classes or, if this situation arises from events that occurred later, should be communicated to the teacher until one week after the facts that support it.

The Jury of the unit is
Ariel Guerreiro
João Lopes Santos
Eduardo Castro

High Performance Computing in Quantum Matter

Link: https://sigarra.up.pt/fcup/en/ucurr_geral.ficha_uc_view?pv_ocorrencia_id=509995

Teaching components (total hours in semester)

T	TP	PL	Total Contact hours	ECTS	Total Hours
	42		42	6	

Lecturers

João Manuel Viana Parente Lopes (jlopes@fc.up.pt)

Goals

Learn the main concepts of parallel programming and be exposed to advanced quantum computing algorithms.

Learning Outcomes and Skills

Being able to interpret a problem, translate it into numerical methods, choose the parallelization approach, implement using parallelization techniques and manage the processes in an HPC infrastructure.

Pre-requisites

Knowledge of Quantum Mechanics, Statistical Physics, Solid State Physics, numerical methods, and C (or C++) programming.

Subject Matter

Key ideas of HPC and parallelization architectures. Introduction to OpenMP.
Domain decomposition. Spectral methods and exact diagonalization methods.
Introduction to MPI. Introduction to CUDA.
Study of electronic transport problems, with and without disorder, in independent electron systems.
Monte Carlo method stochastic series expansion, exact diagonalization, and the determinant method.

Main Bibliography

[...]

Complementary Bibliography

[...]

Teaching Methods and Learning Activities

Theoretical classes with the exposition of contents. Practical lessons with the computational implementation of the proposed problems.

Key words

[...]

Description of assessment

Class participation	10%
Written project	70%
project presentation	20%

During the semester, 3 written works will be done to be delivered. Of these works,

- Two will be shorter and will have the form of a guided project and will be evaluated with 20% each.
- The third will take the form of a project and must be presented in the form of a written work (30%) with oral exam (20%).

The activity in the practical classes will be evaluated by 10%.

Observations

[...]

Quantum matter

Link: https://sigarra.up.pt/fcup/en/ucurr_geral.ficha_uc_view?pv_ocorrencia_id=509994

Teaching components (total hours in semester)

T	TP	PL	Total Contact hours	ECTS	Total Hours
--	42	--	42	6	162

Lecturers

João Manuel Borregana Lopes dos Santos (jlsantos@fc.up.pt)

Vitor Manuel Pereira (vmpereir@fc.up.pt)

Goals

To develop skills for understanding the features and models of the electrical, optical, magnetic, and transport properties of quantum materials, with emphasis on two-dimensional materials and quantum condensed materials (condensates and superconductors).

To empower students for independent and critical assessment of the current literature, and to provide tools for subsequent research and/or technological development activities in the physics and applications of quantum materials.

Learning Outcomes and Skills

Become acquainted with key physical properties, phenomena and representative materials that underpin the current and envisaged implementation of quantum technologies.

Develop a good perspective of the unique features of 2D materials and of many-body condensed states, with an eye on the opportunities they provide for exploring novel and intrinsically quantum-mechanical phenomena.

Understand fundamental models and concepts of the theoretical description of these materials, and acquire skills to independently apply or extend such models.

Understand the relations between the physics that underlines the properties of a material and the technologies and devices it enables.

Develop know-how and skills to engage effectively and in depth with the current research literature on these materials, the underlying phenomena, and their applications.

Subject Matter

1. Two-dimensional materials

    Examples, production, overview of mechanical, electronic, transport and optical properties. Electronic structure models. Tight-binding and effective low-energy models. Electronic structure of single layers, bilayers and multilayers. Twisted 2D crystals. Phonons in 2D materials. Confined electrons in 2D nanostructures, nano-ribbons and quantum dots. Device applications.

2. Quantum magnetism

Origin of exchange interactions. Spontaneous symmetry breaking, ferro- and anti-ferromagnetism. Magnetic ground states and excitations. Novel magnetic states in 2D materials.

3. Condensed materials I: Bose-Einstein condensates

Broken gauge symmetry. Order parameter and superfluity. Fundamental properties. Condensate motion and phase of the order parameter. Quantization of vorticity.

4. Condensed materials II: superconductors

Broken gauge symmetry of charged particles and the Higgs-Anderson mechanism. Ginzburg-Landau theory. Meissner effect. Superconductors of type I and type II. Cooper instability and BCS theory. Ground state and excitations. Josephson's effect, SQUIDS and their applications. Superconductor devices. Particulars and unsolved questions of superconductivity in 2D, and current forefront experiments using 2D materials.

Main Bibliography

1. J M B Lopes dos Santos, Course notes. Unpublished.
2. S. M. Girvin & K. Yang, Modern Condensed Matter Physics. Cambridge University Press (2019).
3. M. Katsnelson, The Physics of Graphene. Cambridge University Press (2020).
4. P. Avouris, T. Heinz, & T. Low (Eds.). 2D Materials: Properties and Devices. Cambridge University Press (2017).
5. J. F. Annett, Superconductivity, superfluids, and condensates. Oxford University Press (2004).
6. S. Blundell, Magnetism in condensed matter. Oxford University Press (2001).

Complementary Bibliography

1. Research and review articles and other readings to be distributed during the course.
2. A. Zagoskin. *Quantum Engineering: Theory and Design of Quantum Coherent Structures*. Cambridge University Press (2011).
3. N. W. Ashcroft & D. N. Mermin. *Solid State Physics*. Brooks Cole (1986).
4. G. Mahan, *Condensed matter in a nutshell*. Princeton University Press (2011).
5. P. W. Anderson. *Concepts in solids*. Benjamin/Cummings (1963).
6. J. M. Ziman, *Principles of the theory of solids*. Cambridge University Press (1972).

Teaching Methods and Learning Activities

The contact hours blend lecturing and discussion of previously assigned readings. All topics will be illustrated by questions and problems for autonomous practice and consolidation, with solution strategies outlined and discussed in class.

Key words

Quantum materials; 2D materials; quantum magnetism; many-body condensates; superconductivity; quantum technologies; quantum condensed matter theory; electronic, magnetic and structural properties of materials.

Description of assessment

The assessment comprises the submission of a paper (30%) and a final exam (70%). The paper can be prepared individually or in group, and it can take various forms: expand the calculations or details of a published research article; solve an extension problem of models discussed in class; short essay on a topic not lectured in class.

Observations

The scope and literature of this field of research is vast, demanding, and quickly expanding. It justifies lecturing of the fundamental concepts and models that are indispensable for a robust understanding of the materials and phenomena that may be harnessed for quantum technologies. The autonomous resolution of problems is essential for consolidation and hands-on practice with those concepts. The use of assigned readings followed by in-class discussion fosters independence and confidence in the students' engagement with the scientific literature.

Computational Complexity

link: https://sigarra.up.pt/fcup/en/ucurr_geral.ficha_uc_view?pv_ocorrencia_id=507418

Teaching components (total hours in semester)

T	TP	PL	Total Contact hours	ECTS	Total Hours
	42		42	6	162

Lecturers

Rogério Ventura Lages dos Santos Reis (rvreis@fc.up.pt)

Goals

We will study some techniques that prove or suggest that there are no known eficient method to solve some important problems in computer science. We will study several complexity classes and their relationship, namely: P, NP, co-NP, PH, RP, BPP, IP.

Learning Outcomes and Skills

Upon successful completion of this course, students will be able to:
(a) Distinguish between complexity classes.
(b) Classify decision problems into appropriate complexity classes, including P, NP, PSPACE and complexity classes based on randomised machine models and use this information effectively.

Subject Matter

1) Motivation and background
2) Complexity classes P and NP
3) Polynomial time hierarchy
4) Class PSPACE and Alternation
4) Non-uniform Models. Boolean Circuits, machines with advice. Class P/poly
5)Randomized complexity classes: RP, BPP and ZPP
6) Interactive protocols, classes IP, AM e MA

Main Bibliography

- Sanjeev Arora and Boaz Barak; Complexity Theory: A Modern Approach
  Oded Goldreich; Computational Complexity: A Conceptual Perspective, Cambridge University Press, 2008. ISBN: 978-0-521-88473-0

Complementary Bibliography

Michael Garey and David Johnson; Computers and intractability: A guide to NP-Completeness, W. H. Freeman, 1979. ISBN: 0716710455
C. Papadimitriou; Computational complexity, Addison Wesley Longman, 1994. ISBN: 0201530821
D.Z. Du and K.I. Ko; Theory of Computational Complexity, John Wiley and Sons, 2000. ISBN: 978-0-471-34506-0

Teaching Methods and Learning Activities

Lectures with practical assignments.

Distributed grading.

Key words

Theoretical Computer Science, Computational Complexity,

Description of assessment

Two tests where the student needs to achieve a mark of 1/3 (in each), and an average of ½ (10/20). Final grade is average of two tests. Remedial evaluation: final exam.

Quantum and Statistical Field Theory

Teaching components (total hours in semester)

T	TP	PL	Total Contact hours	ECTS	Total Hours
	42		42	6	162

Lecturers

Miguel Sousa da Costa (miguelc@fc.up.pt), Vasco David Fonseca Gonçalves (vgoncalves@fc.up.pt)

Goals

Functional Quantisation and Wilsonian Renormalization
Understand functional quantization in quantum field theory and
the concept of renormalization in statistical physics and in quantum field theory. Learn some important models like the quartic scalar field and the non-linear sigma model.

Learning Outcomes and Skills

Adquire the concepts of functional quantisation and of renormalization in field theory and its relevance for statistical physics and particle physics.

Subject Matter

I. Functional quantisation
Path integral in quantum mechanics, functional quantisation of scalar field, Fadeev-Popov method for gauge theories.
II. Renormalization in quantum field theory
Wilsonian renormalization, Wilson-Fisher fixed point, nonlinear sigma model.

Main Bibliography

Michael E. Peskin; An introduction to quantum field theory. ISBN: 0-201-50397-2
Lewis H. Ryder; Quantum field theory. ISBN: 0-521-33859-X
A. M. Polyakov; Gauge fields and strings. ISBN: 3-7186-0393-4

Complementary Bibliography

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Teaching Methods and Learning Activities

TP classes: lectures and worked examples.

Key words

[...]

Description of assessment

Final Exam

Observations

Júri: João Lopes dos Santos, Miguel Costa e Eduardo Castro

Internship Projects

1. Integrated Optic devices fabricated by laser direct writing

Providing Institution

INESCTEC

Place of work

Center of Applied Photonics, Department of Physics and Astronomy, Faculty of Sciences, UPorto

Supervisor(s)

Paulo Marques (psmarque@fc.up.pt) & João Maia

Start date and duration

March 2022; 14 weeks

Goals

After this internship the students will be familiar with the field of integrated optics and optical waveguiding concepts. They should also be familiar with the numerical tools to simulate functional devices. The tasks will be mainly hands-on, so the students will fabricate and test some integrated optic devices by femtosecond laser direct writing.

Learning Outcomes and Skills

After completing the internship, the student should be able to:

- understand the propagation of optical fields in optical waveguides and describe the working principles of the fundamental building blocks components in integrated optics;
- use numerical simulation tools, such as Beam Propagation Methods (BPM);
- know the diverse microfabrication methods, with particular emphasis on the fabrication by femtosecond laser direct writing;
- perform integrated optic devices testing and characterization.

Project description

Integrated optics has been during the last decades gaining a reputation of being a robust platform to implement complex optical processing. The main fabrication technologies rely on standard lithography methods, combined with materials deposition and structuring, all techniques that were borrowed from the semiconductor industry.

Nearly two decades ago, femtosecond laser direct writing has been proposed as an integrated optics fabrication technique which can offer uncommon fabrication attributes: high spatial resolution and

3D fabrication capabilities [1-3]. Additionally, the devices are simply made by a localized refractive index increase within the bulk of a completely uniform substrate, therefore avoiding relying on thin film deposition techniques and lithography. In addition, the technique offers the possibility of high resolution machining by laser ablation or selective anisotropic etching wet-etching induced by laser direct writing.

Integrated optics has proven a reliable technology for the production of active and passive devices, in a plethora of materials ranging from semiconductors to glasses and crystals. Traditionally, these devices are mainly used in optical communications, progressively penetrating into other fields such as optical sensing. More recently, some demonstrations include quantum photonics circuits[4-5].

During this internship the students will become familiar with the principles underlying optical waveguiding and will fabricate some active devices in glasses by femtosecond laser direct writing. The work programme includes first the fabrication and characterization of all the building blocks of an integrated optical modulator. These include the fabrication of low loss optical waveguides (coupling and propagation), S-bends, directional couplers and a Mach-Zhender interferometer. Finally, the active functional part is achieved by adding a thermal shifter over one arm of the interferometer. The heater will be defined by selective ablation of a gold thin film deposited over the substrate. All the buildings blocks will tested and characterized in terms of optical loss, polarization dependence and modulation bandwidth.

Main Bibliography

1. Fernandes, L.A., Grenier, J.R., Herman, P.R., Stewart Aitchison, J., Marques, P.V.S., Stress induced birefringence tuning in femtosecond laser fabricated waveguides in fused silica, (2012) Optics Express, 20 (22), pp. 24103-24114, DOI: 10.1364/OE.20.024103
2. Amorim, V.A., Maia, J.M., Alexandre, D., Marques, P.V.S., Monolithic Add-Drop Multiplexers in Fused Silica Fabricated by Femtosecond Laser Direct Writing, (2017) Journal of Lightwave Technology, 35 (17), art. no. 7949018, pp. 3615-3621, DOI: 10.1109/JLT.2017.2715118
3. Giacomo Corrielli, Simone Atzeni, Simone Piacentini, Ioannis Pitsios, Andrea Crespi, and Roberto Osellame, "Symmetric polarization-insensitive directional couplers fabricated by femtosecond laser writing," Opt. Express 26, 15101-15109 (2018)
4. Corrielli, Giacomo, Crespi, Andrea and Osellame, Roberto. "Femtosecond laser micromachining for integrated quantum photonics" Nanophotonics, vol. 10, no. 15, 2021, pp. 3789-3812. https://doi.org/10.1515/nanoph-2021-0419
5. Flamini, F., Magrini, L., Rab, A. et al. Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining. Light Sci Appl 4, e354 (2015). https://doi.org/10.1038/lsa.2015.127

2. Experimental Optical analogues for the simulation two-dimensional quantum fluids

Providing Institution

INESC TEC

Place of work

Center for Applied Photonics, INESC TEC

Supervisor(s)

Nuno Azevedo Silva (nmasilva@fc.up.pt), Tiago D. Ferreira (up201305729@edu.fc.up.pt)

Start date and duration

March 14 weeks

Goals

We will break the Internship and the study of Quantum Fluids of Light(QFLs) into two operational blocks:

1.Theoretical model: Understand the basic concepts behind the light fluid analogy focusing on the paraxial geometry configuration. Derive the Nonlinear Schrödinger equation(NLSE) and understand the connection to nonlinear optics and quantum fluids, discussing its limitations. Basic review of the state-of-the-art of QFLs in nonlinear optical materials.

2.Development of an experimental case study, either:

a.Exploring quantum turbulence with QFLs – possible experimental verification of [R1];

b.Observation of the Bogoliubov dispersion relation and drag force suppression – possible experimental verification of [R2];

Learning Outcomes and Skills

Quantum simulation is one of the pillars of quantum technologies and concerns the controllable emulation of quantum systems. In this project the students will be introduced to the field of optical quantum fluid analogues, exploring how one can use nonlinear optics to emulate quantum-like phenomena and thus create a quantum simulator. The students will also have contact with experimental setups and methodologies, learning concepts of advanced optical system design and wavefront shaping, and observing nonlinear optics phenomenology with photorefractive crystals.

Project description

The project and research internship aim to introduce the student to the fundamental concepts of Quantum Fluids of Light(QFLs) in an integrated but increasingly autonomous research environment. The training covers mathematical foundations, numerical and computational tools, and hands-on experimental research.

Main Bibliography

[R1] Silva, Nuno Azevedo, Tiago D. Ferreira, and Ariel Guerreiro. "Exploring quantum-like turbulence with a two-component paraxial fluid of light." Results in Optics 2 (2021): 100025.

[R2] Ferreira, Tiago D., Nuno A. Silva, and A. Guerreiro. "Superfluidity of light in nematic liquid crystals." Physical Review A 98.2 (2018): 023825.

[R3] Carusotto, Iacopo. "Superfluid light in bulk nonlinear media." Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 470.2169 (2014): 20140320.

Complementary Bibliography

[R4] Fontaine, Quentin, et al. "Interferences between Bogoliubov excitations in superfluids of light." Physical Review Research 2.4 (2020): 043297.

[R5] Michel, Claire, et al. "Superfluid motion and drag-force cancellation in a fluid of light." Nature communications 9.1 (2018): 1-6.

Key words

Quantum Fuids of Light, Optical Analogues

Description of assessment

[…]

Observations

[...]

3. Designing and Implementing Quantum Algorithms

Providing Institution

University of Porto, Faculty of Engineering

Place of work

Department of Informatics Engineering, Faculty of Engineering of the University of Porto

Supervisor(s)

João Paulo Fernandes (jpaulo@fe.up.pt), Rui Maranhão Abreu (rma@fe.up.pt)

Start date and duration

March, 14 weeks

Goals

The candidate will join a group of researchers who are doing intensive, foundational work on QC. The general goal is to design, implement and analyse algorithms that can leverage quantum properties. In concrete, we aim at reaching the following goals:

- The specification of an algorithm amenable for implementation on a quantum computer.
- The implementation and empirical assessment of the proposed algorithm on a state of the art quantum computer.

Learning Outcomes and Skills

The development of quantum algorithms is particularly challenging since it requires a combination of skills which include, e.g., quantum mechanics and complexity theory, as well as a deep computer science background.
The outcomes of this project will be made publicly available as open source tool sets that can benefit the entire community.
These artifacts will target multiple platforms that are already available for general-purpose quantum computing such as IBM Qiskit or Google's Cirq.

Project description

Quantum Computing (QC) is bound to change the world as we know it.
By exploring the properties of quantum theory for computational purposes, we expect to substantially reduce the amount of problems that are nowadays considered computationally intractable.
This means that Quantum Computers have the power of providing solutions for some of the problems of practical interest for which a Classical Computer cannot, at least in a timely manner.
This is even more revolutionary and remarkable given the fact these problems range from multidisciplinary domains such as Chemistry, Medicine, Routing and Finance.
In this project, we will analyse, propose and implement data structures that are amenable to be executed in quantum computers.

We subscribe to the work of Niklaus Wirth, who in 1976 coined a famous equation in Computer Science - ‘Algorithms + Data Structures = Programs’, and in this case we will focus on the algorithmic counterpart of the equation.
Quantum computation models have originally been studied in the 1980s and algorithms to explore quantum computing started appearing in the early 1990s, even if back then quantum computational devices were essentially theoretical.
Two of the most well known quantum algorithms are Shor’s polynomial-time algorithm for prime factorization and discrete logarithm and Grover’s algorithm that can efficiently search data in an unstructured database.
While the groundbreaking nature of these well known algorithms can not be denied, a challenge that we face here is that they are not possible to be executed in the near-term.
While NISQ hardware implementations (of less than a hundred qubits) have recently been developed, their limitations pose significant challenges regarding the development of practical algorithms, the ones we propose to target.
Nevertheless, a number of NISQ algorithms have already been proposed, namely the Variational Quantum Eigensolver and the Quantum Approximate Optimization Algorithm, which demonstrate the feasibility of the approach.

Main Bibliography

- Shor, P.: Algorithms for quantum computation: Discrete logarithms and factoring. In: Proc. of the 35th Annual Symposium on Foundations of Computer Science, pp. 124–134 (1994)
- Grover, L.: A fast quantum mechanical algorithm for database search. In: Proc. of the 28th ACM Symposium on Theory of Computing, pp. 212–219 (1996)
- Peruzzo, A. et al.: A Variational Eigenvalue Solver on a Photonic Quantum Processor. Nature Communications 5.1 (2014)
- Farhi, E. et. al.: A Quantum Approximate Optimization Algorithm Applied to a Bounded Occurrence Constraint Problem (2014)

Complementary Bibliography

- Wirth, N.: Algorithms & data structures. Prentice-Hall, Inc., (1976).
- F. Leymann, J. Barzen. The bitter truth about gate-based quantum algorithms in the NISQ era, Quantum Science and Technology 5 (4), 044007

Key words

Quantum Computing, Algorithms

Description of assessment

The assessment will seek to evaluate the student competencies regarding their:

- Knowledge on the current overall landscape of quantum computing languages and frameworks;
- Ability to design and implement new, or improved, algorithms in quantum of quantum/classical hybrid settings;
- Ability to assess the merits of the newly proposed algorithms.

Observations

There exists the possibility for the student to work with international colleagues doing research on similar topics.

4. Developing DNA hybrids for quantum coherent energy harvesting and transfer

Providing Institution

INL - International Iberian Nanotechnology Laboratory

Place of work

INL - International Iberian Nanotechnology Laboratory

Supervisor(s)

Dr. Jana Nieder, Ultrafast Bio- and Nanophotonics Research Group, jana.nieder@inl.int

Start date and duration

To be defined (flexible) from 3 months up to 12 months

Goals

Develop DNA dye hybrids, study J- aggregate formation using steady state and time resolved spectroscopy
Analyse the quantum coherence nature of energy transfer and characterize the energy transfer properties on ensemble and single molecular wire level of DNA hybrids.
Report in frame of group seminars and in feedback with supervisors, if applicable presenting results at a conference and writing of the Master thesis document.

Learning Outcomes and Skills

The student should develop an understanding of the exciton distribution across the synthesized molecular wires of DNA hybrids and analysis of quantum coherence nature of energy transfer and characterize the energy transfer properties on ensemble and singles molecular wire level

Project description

The phenomenon of light migration via resonant energy transfer is of fundamental importance in nature. In photosynthetic organisms, light is absorbed by pigments located in the light-harvesting complexes (LHCs) and then transferred through different mechanisms to the reaction centre, where the photons' energy is transformed into chemical energy. To understand and mimic the natural process of light-harvesting, it is beneficial to construct artificial systems that efficiently control the transport of light [1]. The ability to use DNA as a template to arrange functional elements such as organic dyes into specific arrays has undergone remarkable development over the last few decades. Recently, such chromophore-labelled DNA structures have been successfully employed to create photonic wires and antenna systems, marking the advent of DNA nanotechnology in the field of artificial photosynthesis. The DNA structure as a programmable scaffold potentially provides a means for integrating directional energy transfer through templated aggregates with other photonic components that supply or use excitation energy. DNA hybrids have been demonstrated to mediate energy transfer between donor and acceptor molecules attached to either DNA ends, allowing the energy to be transferred from the excited donor dye through a number of identical transmitter dyes to a single acceptor fluorophore [2, 3]. It is envisaged characterization of quantum wires with strong interchromophoric couplings, the study of coupling and dynamic properties and quantum coherent energy transfer on single micro-/nanowires via advanced fluorescence microscopy as described in Ref [4]. A Widefield /TIRF microscope shall be used. For local excitation and widefield detection a modification at the microscope excitation path will be developed. The relative distance from excitation to emission spots on the sample shall be analysed. It should be used an excitation energy transfer model to quantify the energy transfer distance and delocalization of excitation along the nanowire, as the model described in the Ref 5. Spano-Model is an extended exciton model with an approach based on one- and two-particle states for the involved chromophores. This way, the image data shall be used to analyse if a quantum coherent energy transfer process is achieved.

This deep understanding has the potential to improve the EET behavior of artificial quantum wires with applications in optoelectronics, plasmonics, and efficient artificial light-energy harvesting systems.

Main Bibliography

[1] F. Nicoli et al, ACS Nano 2017 11 (11), 11264-11272, DOI: 10.1021/acsnano.7b05631
[2] X. Zhou et al, Journal of the American Chemical Society 2019 141 (21), 8473-8481, DOI: 10.1021/jacs.9b01548
[3] J. L. Banal e al, Photophysics of J-Aggregate-Mediated Energy Transfer on DNA, The Journal of Physical Chemistry Letters 2017 8 (23), 5827-5833, DOI:10.1021/acs.jpclett.7b01898
[4] B. Wittmann et al, J. Am. Chem. Soc. 2020, 142, 18, 8323–8330, https://doi.org/10.1021/jacs.0c01392
[5] A.T. Haedler et al, Nature 2015, 523, 196–199. https://doi.org/10.1038/nature14570.

Complementary Bibliography

[1] G. D. Scholes, The journal of physical chemistry letters 2010, 1,2-8, DOI: 10.1021/jz900062f
[2] A. Thilagam, J Math Chem 2015 53:466–494, DOI 10.1007/s10910-014-0442-x
[3] T. Mirkovic, Chemical Reviews 2017, 117, 249-293, DOI 10.1021/acs.chemrev.6b00002
[4] K.Hyeon-Deuk, The jorunal of chemical Physics 2007 127, 075101, DOI: 10.1063/1.2754680

Key words

Quantum coherent energy transfer; molecular aggregates; DNA; J-aggregates, Time resolved spectroscopy (...)

Description of assessment

Independency performing experimental work (after dedicated training provided by team members), written project report and oral presentation of the results at the group seminar. Plus: ability to discuss the project in context of the state of the art as well as identifying arising opportunities based on experimental observations.

Observations

The candidate’s project will be inserted in ongoing research project related to the development of Quantum wires for efficient energy transfer – a 4 years project developed mainly by PhD candidate

Maria-João Lopes in the group of Ultrafast Bio- and Nanophotonics group at INL, an interdisciplinary team comprising chemists, physicists and phys. engineers among others.

5. Quantum Light Sources: Effects of the local environment on the photo-dynamics and emission spectra of hBN single photon emitters

Providing Institution

INL – International Iberian Nanotechnology Laboratory

Place of work

INL - International Iberian Nanotechnology Laboratory

Supervisor(s)

Dr. Jana Nieder, Ultrafast Bio- and Nanophotonics Research Group, jana.nieder@inl.int

Start date and duration

To be defined (flexible) from 3 months up to 12 months

Goals

Perform experiments to better understand the mechanisms behind fluorescence flickering in hBN single photon emitters (SPEs), more specifically the tasks will involve:
- Preparation of hBN samples by polymer assisted wet transfer of CVD grown hBN onto glass coverslips with different material coatings, such as alumina, gold, etc…
- Characterization of emitter surface densities in hBN and their fluorescence flickering behaviours via total internal reflection fluorescence microscopy under several local environment conditions;
- Characterization of the emission spectra of hBN SPEs and the spectral shifts experienced in the presence of different materials by using confocal fluorescence microscopy in a lambda mode configuration;
- Characterization of how the emission lifetimes of hBN SPEs are modified in the presence of different solvents and materials;

Learning Outcomes and Skills

Quantum measurements related to single photon emitters;
"Single molecule" fluorescence microscopy techniques geared towards light emitting single point defects using total internal reflection fluorescence (TIRF) microscopy, hyperspectral confocal fluorescence microscopy , and fluorescence lifetime imaging microscopy (FLIM);
Data analysis methods of fluorescence microscopy data (STORM and MATLAB/Python scripting);
Handling and characterization of 2D materials (2D material wet transfer and Raman spectroscopy);

Project description

Single photon emitter (SPE) defects in wide band-gap materials like diamond and hexagonal Boron Nitride (hBN) have received continuously larger attention due to their potential for quantum technologies and probing matter at the nanoscale. One of the hurdles that have to be overcome for the implementation of hBN in these applications is the innate fluorescence flickering of its defects,

often called blinking. Early successful strategies at suppressing blinking include applying a bias voltage or transferring the hBN to a layer of passivating material such as Al2O3, which can impose restrictions on device fabrication. A way to reduce these restrictions is to increase the number of available passivation materials.
Recently, it was found that SPEs in hBN can be activated in the presence of organic solvents and that their emission properties, such as the main emission peak, could be altered based on the type of organic solvents. We propose a project where the student would characterize the photo-emission of SPEs in CVD grown hBN samples under various local environmental conditions, such as the substrate's material and capping the sample with polar and nonpolar solvents, as a way to explore new options for controlling the emission properties of hBN SPEs.

Main Bibliography

I. A. Milos Toth, "Single Photon Sources in Atomically Thin Materials," Annu. Rev. Phys. Chem., vol. 70, pp. 123–142, 2019, doi: https://doi.org/10.1146/annurev-physchem-042018-052628.
M. K. Boll, I. P. Radko, A. Huck, and U. L. Andersen, "Photophysics of quantum emitters in hexagonal boron-nitride nano-flakes," Opt. Express, vol. 28, no. 5, p. 7475, 2020, doi: 10.1364/oe.386629.
H. L. Stern et al., "Spectrally Resolved Photodynamics of Individual Emitters in Large-Area Monolayers of Hexagonal Boron Nitride," ACS Nano, vol. 13, no. 4, pp. 4538–4547, 2019, doi: 10.1021/acsnano.9b00274.
N. Mendelson et al., "Engineering and Tuning of Quantum Emitters in Few-Layer Hexagonal Boron Nitride," ACS Nano, vol. 13, no. 3, pp. 3132–3140, 2019, doi: 10.1021/acsnano.8b08511.
X. Li et al., "Nonmagnetic Quantum Emitters in Boron Nitride with Ultranarrow and Sideband-Free Emission Spectra," ACS Nano, vol. 11, no. 7, pp. 6652–6660, 2017, doi: 10.1021/acsnano.7b00638.

Complementary Bibliography

M. Kianinia et al., "All-optical control and super-resolution imaging of quantum emitters in layered materials," Nat. Commun., vol. 9, no. 1, 2018, doi: 10.1038/s41467-018-03290-0.
B. Sontheimer, M. Braun, N. Nikolay, N. Sadzak, I. Aharonovich, and O. Benson, "Photodynamics of quantum emitters in hexagonal boron nitride revealed by low-temperature spectroscopy," Phys. Rev. B, vol. 96, no. 12, pp. 1–5, 2017, doi: 10.1103/PhysRevB.96.121202.
A. Basha and P. Palla, "Optical quantum technologies with hexagonal boron nitride single photon sources," Sci. Rep., pp. 1–27, 2021, doi: 10.1038/s41598-021-90804-4.
Mark Fox, "Quantum Optics: An Introduction", Oxford Master series in Physics, OUP Oxford, 2006, Volume 15
J. Comtet et al., "Wide-Field Spectral Super-Resolution Mapping of Optically Active Defects in Hexagonal Boron Nitride," Nano Lett., vol. 19, no. 4, pp. 2516–2523, 2019, doi: 10.1021/acs.nanolett.9b00178.
C. Li, N. Mendelson, R. Ritika, Y. Chen, Z. Xu, and M. Toth, "Scalable and Deterministic Fabrication of Quantum Emitter Arrays from Hexagonal Boron Nitride," no. Cvd, pp. 25–28, 2007.
T. T. Tran et al., "Resonant Excitation of Quantum Emitters in Hexagonal Boron Nitride," ACS Photonics, vol. 5, no. 2, pp. 295–300, 2018, doi: 10.1021/acsphotonics.7b00977.

Key words

Single Photon emitters, Quantum information, quantum photonics, 2D Materials, Nanophotonics

Description of assessment

Independently performing experimental work (after dedicated training provided by team members), written project report and oral presentation of the results at the group seminar. Plus: ability to discuss the project in context of the state of the art as well as identifying arising opportunities based on experimental observations.

Observations

The candidate's project will be inserted in ongoing research project related to the development of Single Photons On-Demand from a 2D material heterostructure - Tiago Queirós in the group of Ultrafast Bio- and Nanophotonics group at INL, an interdisciplinary team comprising chemists, physicists and phys. engineers among others.

6. 3D Diamond-Photonic Platforms for Quantum Metrology

Providing Institution

INL – International Iberian Nanotechnology Laboratory

Place of work

INL - International Iberian Nanotechnology Laboratory

Supervisor(s)

Dr. Jana Nieder, Ultrafast Bio- and Nanophotonics Research Group, jana.nieder@inl.int

Start date and duration

To be defined (flexible) from 3 months up to 12 months

Goals

- Learn the fundaments of both nanodiamonds (NDs) physical properties and an Optically Detected Magnetic Resonance (ODMR) experimental setup
- Learn the fundaments of fabricating 3D polymeric structures and the grafting of NDs
- Perform and optimize 2D and 3D ODMR measurements on given samples
- Report in frame of group seminars and in feedback with supervisors, if applicable presenting results at a conference and writing of the Master thesis document.

Learning Outcomes and Skills

- Basic knowledge on the optical properties of NDs and ODMR, as well as on the fabrication and grafting NDs on 3D structures
- Interaction with a fully developed ODMR setup and experiments performance
- Working in an international research team at an intergovernmental research organization, experience presenting research outcomes in group seminars and, if applicable, in conferences or in form of a co-authored scientific publication

Project description

The nitrogen-vacancy (NV) centers in nanodiamonds (NDs) are singular electronic structures that allows to study and manipulate the quantum state of the spin. An Optically Detected Magnetic Resonance (ODMR) experimental setup allows for the detection of spin state shifts trough differences in the red fluorescence intensity emitted by nanodiamonds when excited by a 532 nm or 561 nm laser. The study of ODMR traces can also allow for the detection of magnetic fields and temperature changes.

Characterization of Magnetic Nanostructures allows the familiarization with ODMR measurements using nanodiamonds. The development of 3D ODMR measurements was never reported and if accomplished, will potentially enable the measurement of electrical signals from neurons seeded in 3D structures.

Grafting the 3D polymeric structures’ surface with the biocompatible NDs would allow a nanoscale proximity of neurons adhering to the scaffolds, creating a sensitive platform for both electrical signaling and temperature shifts. The proximity is key for the measurement of these parameters, in accordance with the sensitivity of the ODMR technique.

Main Bibliography

[1] F. Barry et al., Proc. Natl. Acad. Sci., vol. 114, no. 32, pp. E6730–E6730, Aug. 2017, doi: 10.1073/pnas.1712523114.
[2] R. Schirhagl et al., Annu. Rev. Phys. Chem., vol. 65, no. 1, pp. 83–105, Apr. 2014, doi: 10.1146/annurev-physchem-040513-103659.
[3] L. T. Hall et al., Sci. Rep., vol. 2, no. 1, p. 401, Dec. 2012, doi: 10.1038/srep00401.
[4] S. Choe et al., Curr. Appl. Phys., vol. 18, no. 9, pp. 1066–1070, Sep. 2018, doi: 10.1016/j.cap.2018.06.002.
[5] F. Camarneiro, et al., Part. Part. Syst. Charact., 38, 2100011, Jul. 2021, doi: 10.1002/ppsc.202100011

Complementary Bibliography

[1] B. N. L. Costa et al., ACS Applied Materials & Interfaces, 14, 13013–13024, Mar. 2022, doi: 10.1021/acsami.1c23442
[2] F. Morales-Zavala et al., J. Nanobiotechnology, vol. 16, no. 1, p. 60, Dec. 2018, doi: 10.1186/s12951-018-0385-7.
[3] N. Chen, G. Gao, and S. Poh, “Focal Modulation Microscopy: Principle and Techniques,” in Molecular Imaging, no. June 2014, InTech, 2012.
[4] Žukauskas et al., Lith. J. Phys., vol. 50, pp. 55–61, 2010, doi: 10.3952/lithjphys.50112.

Key words

Nanodiamonds, Nitrogen-vacancy centers, Optically detected magnetic resonance, Three-dimensional

Description of assessment

Independency performing experimental work (after dedicated training provided by team members), written project report and oral presentation of the results at the group seminar. Plus: ability to discuss the project in context of the state of the art as well as identifying arising opportunities based on experimental observations.

Observations

The candidate’s project will be inserted in ongoing research project related to the development of Diamond Photonics platform in frame of the Diamond4Brain project, funded by “la Caixa” Foundation and FCT and related to ongoing PhD research project conducted by Beatriz Costa on “Development of Three-Dimensional Diamond Photonics Platforms for Neuronal Research “, also funded by the project. The master internship shall be executed in the group of Ultrafast Bio- and Nanophotonics at INL, in an interdisciplinary team comprising physicists and phys. engineers, chemists, among others.

7. Quantum metrology platform: Creating Nitrogen Vacancy (NV) centers in diamond using a femtosecond laser in combination with plasmonic effects

Providing Institution

INL – International Iberian Nanotechnology Laboratory

Place of work

INL - International Iberian Nanotechnology Laboratory

Supervisor(s)

Dr. Christian Maibohm and Dr. Jana Nieder, Ultrafast Bio- and Nanophotonics Research Group
christian.maibohm@inl.int and jana.nieder@inl.int

Start date and duration

To be defined (flexible) from 3 months up to 12 months

Goals

Learn about quantum metrology concepts based on NV centers in diamond, and their creation using fs lasers. Perform experiments to identify the best conditions for the deterministic creation of colour centres in a diamond bulk crystal using a femtosecond laser.

- Optimization of NV center creation in diamond by measuring the fluorescence emission properties of the diamond sample after fs laser treatment.

To optimize the fs laser writing process the following parameters may be optimized during the internship:

a) the excitation laser power and laser wavelength

b) using compressed and uncompressed pulses

c) in the presence of resonant plasmonic nanoparticles deposited on the surface of the diamond substrate

d) in dependence of the size or shape and material of the plasmonic metal nanostructures deposited on the diamond surface

Learning Outcomes and Skills

- Knowledge on the optical properties of color centers in diamond
- Femtosecond laser-based material processing
- Fluorescence detection, including single emitter detection tests
- Plasmonic and field enhancement
- Quantum metrology based on Nitrogen Vacancy centres in diamond

- Working with a femtosecond laser and advanced fluorescence detection set ups, working in an international research team at an intergovernmental research organization,
- Experience presenting research outcomes in group seminars and, if applicable, in conferences or in form of a co-authored scientific publication

Project description

The DIAMOND-CONNECT project led by INL builds on the advances in quantum metrology based on diamond photonics for magnetic field sensing. The planned experiments in the project aims to advance and increase understanding of core processes in the functioning of the brain, focusing on neuronal signaling, and connectivity by the development and application of a novel diamond photonics platform.
A femtosecond laser shall be used to create optically active atom-scale sensors at specific locations in a diamond crystal lattice. The sensor pattern shall be optimized for the sensing of magnetic signals created by a stimulated network of neuronal cells.

Nitrogen-vacancy (NV) centers in diamond are optical defects that have been used in a myriad of fields such as quantum information as a qubit, in quantum sensing as the optical sensing element, and in cryptography as a single photon emitter [1].
Typically, NV centers in diamond are created by electron or nitrogen ion irradiation with subsequent annealing. However, these techniques lack NV number control and placement precision [2]. In the last decade, ultrashort pulse laser irradiation with a subsequent annealing process has surfaced as an alternative to the aforementioned technique [3]. NV fs-laser creation as shown near unity yield and sub-micrometer placement precision [4].
Plasmonic structures should also be applied to enhance the field produced by the femtosecond laser, greatly enhancing the interaction between light and the material [5]. Recently, microstructures (in form of Solid immersion lenses [6]), or nanostructured materials such as SiO2 nanoballs [7] have been used to increase the laser focusing in the context of NV center creation. In this project’s scope, plasmonic structures shall be applied to enhance the NV writing potential of the fs-laser.

Main Bibliography

[1] M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. L. Hollenberg, “The nitrogen-vacancy colour centre in diamond,” Physics Reports, vol. 528, no. 1. pp. 1–45, Jul. 01, 2013, doi: 10.1016/j.physrep.2013.02.001.
[2] A. Haque and S. Sumaiya, “An overview on the formation and processing of nitrogen-vacancy photonic centers in diamond by ion implantation,” Journal of Manufacturing and Materials Processing, vol. 1, no. 6. MDPI, Aug. 25, 2017, doi: 10.3390/jmmp1010006.
[3] Y.-C. Chen et al., “Laser writing of coherent colour centres in diamond,” Nat. Photonics, vol. 11, no. 2, pp. 77–80, 2017, doi: 10.1038/nphoton.2016.234.
[4] Y.-C. Chen et al., “Laser writing of individual nitrogen-vacancy defects in diamond with near-unity yield,” Optica, vol. 6, no. 5, p. 662, May 2019, doi: 10.1364/optica.6.000662.
[5] H. Yu, Y. Peng, Y. Yang, and Z. Li, “Plasmon-enhanced light–matter interactions and applications,” npj Comput. Mater., vol. 45, no. March, pp. 1–14, 2019, doi: 10.1038/s41524-019-0184-1.
[6] V. Yurgens et al., “Low-Charge-Noise Nitrogen-Vacancy Centers in Diamond Created Using Laser Writing with a Solid-Immersion Lens,” ACS Photonics, vol. 8, no. 6, pp. 1726–1734, Jun. 2021, doi: 10.1021/acsphotonics.1c00274.

[7] Youying Rong et al "Efficient generation of nitrogen vacancy centers by laser writing close to the diamond surface with a layer of silicon nanoballs", 2020 New J. Phys. 22 013006, doi.org/10.1088/1367-2630/ab6351

Complementary Bibliography

Y. Liu et al., "Fabrication of nitrogen vacancy color centers by femtosecond pulse laser illumination," Opt. Express, vol. 21, no. 10, p. 12843, 2013, doi: 10.1364/oe.21.012843.
S. M. Pimenov, A. A. Khomich, B. Neuenschwander, B. Jäggi, and V. Romano, "Picosecond-laser bulk modification induced enhancement of nitrogen-vacancy luminescence in diamond," J. Opt. Soc. Am. B, vol. 33, no. 3, p. B49, 2016, doi: 10.1364/josab.33.000b49.
V. V. Kononenko et al., "Nitrogen-vacancy defects in diamond produced by femtosecond laser nanoablation technique," Appl. Phys. Lett., vol. 111, no. 8, pp. 1–5, 2017, doi: 10.1063/1.4993751.
J. P. Hadden et al., "Integrated waveguides and deterministically positioned nitrogen vacancy centers in diamond created by femtosecond laser writing," Opt. Lett., vol. 43, no. 15, p. 3586, 2018, doi: 10.1364/ol.43.003586.
C. J. Stephen et al., "Deep Three-Dimensional Solid-State Qubit Arrays with Long-Lived Spin Coherence," Phys. Rev. Appl., vol. 12, no. 6, Dec. 2019, doi: 10.1103/PhysRevApplied.12.064005.

Key words

NV centers in diamond, laser fabrication, Quantum information, quantum photonics, plasmonics

Description of assessment

Independency performing experimental work (after dedicated training provided by team members), written project report and oral presentation of the results at the group seminar. Plus: ability to discuss the project in context of the state of the art as well as identifying arising opportunities based on experimental observations.

Observations

The candidate's project will be inserted in ongoing research project related to the development of Diamond Photonics platform in frame of the DIAMOND-CONNECT FCT funded project and related to ongoing PhD research project conducted by Joao Paulo Silva on "Development of nitrogen-vacancy centre arrays in diamond for neuronal signaling studies", also funded by the FCT. The master internship shall be executed in the group of Ultrafast Bio- and Nanophotonics at INL, in an interdisciplinary team comprising physicists and phys. engineers, chemists, among others.