XXXI International Summer School "Nicolás Cabrera"

Quantum photonic technologies: A new realm for communication and information processing

HI BOB

31/08 - 05/09/2025
Miraflores de la Sierra
Madrid (Spain)

INVITED SPEAKERS

Gerhard Rempe
Costanza Toninelli
Eleni Diamanti
José Capmany
Hugues de Riedmatten
Sarah Thomas
Andrea Litvinov
Alejandro González Tudela
Ignacio Cirac
Hugo Defienne
Alexander Lvosvky
Quandela (Niccolo Somaschi)
LuxQuanta (Valerio Pruneri)
Qilimanjaro (Marta P. Estarellas)
Multiverse Quantum Computing (Román Orús)

ORGANIZING COMMITTEE

Maria Dolores Martín
J. Vicente Vidal Martinez-Pons
Christos Paspalides
Pablo Vaquer de Nieves

ORGANIZERS

Carlos Antón-Solanas
Luis Viña

https://www.inc.uam.es/summer-school-2025/

Design by No-nonsense Labs / Pablo Matera

UAM Universidad Autónoma de Madrid | Instituto Nicolás Cabrera | International Year of Quantum Science and Technology | Fundación BBVA

Contents

Aims and scope

The International Summer School "Nicolás Cabrera" series, supported by the BBVA Foundation, has been addressing cutting-edge topics in materials science, condensed matter, and material physics since 1994. The school gathers scientists from around the world for a few days of intense scientific exchange in a uniquely pleasant and interactive environment.

The 31st edition, which takes place during the **2025 International Year of Quantum Science and Technology**, will focus on quantum technologies, with a special emphasis on light-based platforms. Quantum photonics enables revolutionary advances in secure communication, high-precision metrology, simulation and computation, with photons as key building blocks for the development of quantum applications.

The program will cover five core topics:

1. **Sources of quantum light**
2. **Quantum communication & storage**
3. **Quantum simulation & computation**
4. **Quantum imaging**
5. **Optical neural networks**

The lectures will be given by leading researchers and industry representatives, who will also share insights into innovation, startups, and professional opportunities in the European quantum ecosystem. The school is aimed at PhD students, as well as postdoctoral researchers.

The school will take place at the Residence "La Cristalera" in Miraflores de la Sierra, a village 50 km from Madrid, from **Monday, September 1st to Friday, September 5th, 2025**, with arrival and welcome reception on **Sunday, August 31st**. A shuttle service between Madrid (city centre and airport) and the venue will be provided.

Organizers

Organizers:

Carlos Antón Solanas, UAM

Luis Viña Liste, UAM

Local organizing committee:

María Dolores Martín, UAM

Juan V. Vidal Martínez-Pons, UAM

Christos Paspalides, UAM

Pablo Vaquer de Nieves, UAM

Contact details:

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Supported by:

Fundación BBVA

Invited speakers

Alexander LVOVSKY, University of Oxford, UK

Gerhard REMPE, Max Planck Institute of Quantum Optics, Germany

Costanza TONINELLI, National Institute of Optics, CNR, Italy

Andrea LITVINOV, IQOQI and Austrian Academy of Sciences, Austria

José CAPMANY, Universidad Politécnica de Valencia, Spain

Alejandro GONZÁLEZ TUDELA, Instituto de Física Fundamental, CSIC, Spain

Ignacio CIRAC, Max-Planck-Institute of Quantum Optics, Germany

Eleni DIAMANTI, CNRS, Université Pierre et Marie Curie, France

Sarah THOMAS, Balliol College, University of Oxford, UK

Hugues de RIEDMATTEN, Institute of Photonic Sciences, Spain

Hugo DEFIENNE, CNRS, Sorbonne University, France

Niccolo SOMASCHI, Quandela SAS (CEO), France

Marta P ESTARELLAS, Qilimanjaro Quantum Tech (CEO), Spain

Román ORÚS, Multiverse Quantum Computing (CSO), Spain

Samael SARMIENTO, LuxQuanta (R&D Engineer), Spain

Venue and travel information

LA CRISTALERA RESIDENCE

La Cristalera residence (fuam.es/la-cristalera) is located in Miraflores de la Sierra (miraflоresdelasierra.es), a pleasant mountain resort near Madrid.

The residence is equipped with some sport facilities and a swimming pool. Mountain hiking trails for all levels can be easily accessed from the residence.

Internet can be accessed through EduRoam system (**www.eduroam.org**/) and a wifi network (crisuam), with free access in the dining room.

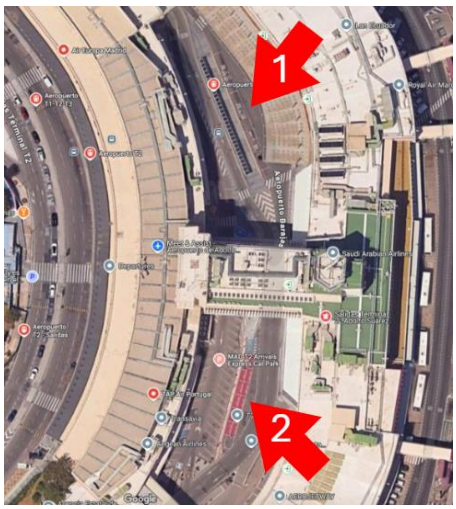
TRAVEL INFORMATION: HOW TO REACH LA CRISTALERA

La Cristalera is located in **Miraflores de la Sierra**, a small town 45 minutes by car North of Madrid city.

A shuttle will be organized between the Terminal 2 of Adolfo Suárez Madrid-Barajas Airport and the residence La Cristalera, with a stop in between, at Paseo de la Castellana 214, with the following schedule:

– Sunday, August 31st

17:00, Airport T2 (Bus bays, position 1 or **Taxi bays**, position 2)



18:00 Pº Castellana, 214 (next to the Churrería "*Michurri*", see arrow) – La Cristalera

19:00 La Cristalera

– Friday, September 5th, 15:30, La Cristalera – Plaza de Castilla – Airport T2

We kindly ask you to plan your arrival in Madrid accordingly.

How to get to Miraflores de la Sierra by public transportation:

There is a bus from Madrid to Miraflores de la Sierra, which leaves from the bus station located in Plaza de Castilla (bus number 725). This bus departs from the "Intercambiador de Transportes de Plaza de Castilla", located in the basement at level -2. The estimated duration of the journey is approximately one hour. The bus stops in the centre of Miraflores de la Sierra. Afterwards, there is a thirty-minute walk to the venue (see the walk) or asking for a taxi is required to reach to the venue La Cristalera (Taxi service in Miraflores de la Sierra: Ángel Redondo, +34 615 278 090).

ALTERNATIVE OPTIONS TO REACH LA CRISTALERA

Arrival by plane:
You can reach Miraflores by taxi from the airport, but this is an expensive choice (around 100€, but please ask before for a price). The information for the driver is: Residencia "La Cristalera" Carretera de Miraflores de la Sierra a Rascafría km 10 (M-611) 28792, Miraflores de la Sierra (Madrid). Tell him to go through "Autovía de Colmenar, M-607". You can also take a taxi from the Airport to Plaza Castilla (33 € fixed fare for Madrid city) and then take a bus (725 line) to Miraflores (see previous paragraph). You can find your way from Madrid guided by Google maps, inserting your departure place and "Miraflores de la Sierra, 28792, Madrid" as the arrival place. Then, there is a 30-minute walk from the city centre of Miraflores to the meeting place with approximately 100 meters of height difference (see the walk).

Arrival by train:
There are two train stations, Chamartín and Atocha. From Chamartín, you can take the Metro (line 1 light blue or line 10: dark blue) to Plaza de Castilla, but it is only one station, and it is also easy to walk from Chamartín to Plaza de Castilla. If you arrive at Atocha, you can take the Metro (line 1: light blue, 15 stations) to Plaza de Castilla. In both cases, follow the above-mentioned instructions for the bus.

Arrival by car:
Take highway M-40. If you come from the south, Portugal, or the Zaragoza Highways, take direction North (N-I). If you come from the Burgos Highway (N-I), take the direction M-607 Tres Cantos- Colmenar Viejo. Go out of the M-40 to the M-607 Highway towards Tres Cantos-Colmenar Viejo. When the Highway ends (roughly 30 km) take the direction of Miraflores. After 30 km, you will reach the village. Once there, follow the signs towards Puerto de la Morcuera, stopping at La Cristalera. One kilometre outside the village, you will find the entrance to the residence on your left (but watch out for it since the sign is not a big one and may be missed). GPS location: 40° 49′ 14″ N, 3° 47′ 1″ W

Schematic program

	Sunday 31st	Monday 1st	Tuesday 2nd	Wednesday 3rd	Thursday 4th	Friday 5th
8:00 9:00		Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
9:00 9:30		**Opening session**				
9:30 11:00		**A. Lvovsky**	**A. Litvinov**	**J.I. Cirac**	**S. Thomas**	**Quandela/ Qilimanjaro**
11:00 11:30		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
11:30 13:00		**G. Rempe**	**J. Capmany**	**E. Diamanti**	**H. de Riedmatten**	**Multiverse/ LuxQuanta**
13:15 15:00		LUNCH & free time	LUNCH & free time	LUNCH & free time	LUNCH & free time	Closure & LUNCH
15:00 16:30		**C. Toninelli**	**A. Gonzalez-Tudela**	Excursion and social dinner (Segovia)	**H. Defienne**	
16:30 17:00		Coffee break	Poster session with drinks and snacks		Coffee break	
17:00 19:00	**Registration**	Oral presentations			Oral presentations	
19:00 20:00	**Welcome reception**	Free time	Free time		Free time	
20:00 -...	DINNER	DINNER	DINNER		BARBACUE	

Opening Session

Welcoming addressed by:

1.- Prof. Amaya Mendikoetxea Pelayo

Rector of the Universidad Autónoma de Madrid (UAM)

2. Prof. Miguel Ángel Ramos Ruiz

Director of the Nicolás Cabrera Institute (INC)

3. Prof. Luis Viña Liste

President of the Spanish Royal Physics Society (RSEF) and co-organizer of the school

4. Dr. Carlos Antón Solanas

Researcher of the INC and co-organizer of the school

Detailed program

Monday 1st		
8:00-9:00	Breakfast	
9:00-9:30	Opening Session	
9:30-11:00 Chair: J. Capmany	**A. Lvovsky**	The many faces of optical neural networks
11:00-11:30	Coffee break	
11:30-13:00 Chair: A. González – Tudela	**G. Rempe**	An entanglement toolbox for quantum photonics
13:15-15:00	Lunch & Free time	
15:00-16:30 Chair: A. Litvinov	**C. Toninelli**	Organic molecules in solids for photonic quantum technologies
16:30-17:00	Coffee break	
17:00-17:20 Chair: J. Abad	**Helmi Fartas**	Reproducible generation of green-emitting color centers in hBN using oxygen annealing
17:20-17:40 Chair: J. Abad	**Quentin Richter**	Few-photon SUPER: Quantum emitter inversion via two off-resonant photon modes
17:40-18:00 Chair: J. Abad	**Anastasiia Zalogina**	Inverse-designed nanophotonic demultiplexer for exciton routing
18:00-18:20 Chair: J. V. Vidal	**Alberto Miguel**	Inverse design of nanophotonic platforms for robust quantum state preparation in driven-dissipative systems
18:20-18:40 Chair: J. V. Vidal	**Susana Plascencia**	Spatially-multiplexed solid-state quantum memory
18:40-20:00	Free time	
20:00-...	Dinner	

Tuesday 2nd		
8:00-9:30	Breakfast	
9:30-11:00 Chair: A. Lvovsky	**A. Litvinov**	Dipolar quantum gases
11:00-11:30	Coffee break	
11:30-13:00 Chair: C. Toninelli	**J. Capmany**	Analog programmable photonic computation and information
13:15-15:00	LUNCH and free time	
15:00-16:30 Chair: S. Thomas	**A. Gonzalez-Tudela**	Quantum simulators combining electrons and photons
16:30-19:00	Poster Session	
19:00-20:00	Free time	
20:00-…	Dinner	

Wednesday 3rd		
8:00-9:30	Breakfast	
9:30-11:00 Chair: H. de Riedmatten	**J.I. Cirac**	Quantum simulation
11:00-11:30	Coffee break	
11:30-13:00 Chair: H. Defienne	**E. Diamanti**	Quantum communication networks
13:15-15:00	Lunch & free time	
15:00-…	Excursion & Social dinner (Segovia)	

Thursday 4th		
8:00-9:30	Breakfast	
9:30-11:00 Chair: G. Rempe	**S. Thomas**	Devices for quantum networks
11:00-11:30	Coffee break	
11:30-13:00 Chair: C. Antón – Solanas	**H. de Riedmatten**	Quantum nodes for quantum repeaters
13:15-15:00	Lunch & free time	
15:00-16:30 Chair: M. D. Martín	**H. Defienne**	Entanglement-enabled quantum imaging
16:30-17:00	Coffee break	
17:00-17:20 Chair: L. Hanschke	**Luis Javier González Martin del Campo**	Versatile entanglement synthesizer for the generation of high-dimensional quantum states
17:20-17:40 Chair: L. Hanschke	**Daniel Montesinos Capacete**	Quantum reservoir computing based on optical memristors
17:40-18:00 Chair: L. Hanschke	**Lorenz Sauerzopf**	On-chip photonic and superconducting circuits for Erbium^{3+} ion property analysis
18:00-18:20 Chair: R. Tichauer	**Maksim Lednev**	Spatially resolved photon statistics of general nanophotonic systems
18:20-18:40 Chair: R. Tichauer	**Eva Schöll**	Electric-field control of photon indistinguishability in cascaded decays in quantum dots
18:40-20:00	Free time	
20:00-...	BARBACUE	

Friday 5th		
8:00-9:30	Breakfast	
9:30-10:15 Chair: C. Antón – Solanas	**Quandela** Niccolo Somaschi	Modular and networked quantum computing based on spin-optical interfaces
10:15-11:00 Chair: C. Antón – Solanas	**Qilimanjaro** Marta P. Estarellas	Analog quantum computers and hybrid data centers to fast-track quantum advantage and unlock global access
11:00-11:30	Coffee break	
11:30-12:15 Chair: L. Viña	**Multiverse** Román Orús	Multiverse computing: quantum and AI
12:15-13:00 Chair: L. Viña	**LuxQuanta** Samael Sarmiento	Towards secure networks using CV-QKD
13:15-15:00	Closure & Lunch	

Abstracts of talks

THE MANY FACES OF OPTICAL NEURAL NETWORKS

Alexander LVOVSKY

University of Oxford, Clarendon Laboratory, Oxford, United Kingdom

Optical neural networks (ONNs) harness the fundamental properties of light to enable ultrafast, energy-efficient computation, surpassing the limitations of digital-electronic systems in tasks such as large-scale matrix multiplications. By exploiting interference, diffraction, and nonlinearity, ONNs can perform parallel processing of high-dimensional data, reducing latency and power consumption. This talk explores three complementary perspectives on ONNs. First, we discuss ONN applications for machine learning and our recent results on training an ONN by propagating light backwards through its layers. Second, we show how an ONN can be applied for spatial mode decomposition of an optical field, enabling the extraction of spatial information beyond the classical diffraction limit by leveraging the quantum and classical correlations in the field. Finally, we discuss coherent Ising machines, in which an optical network with feedback finds minimum-energy gates of interacting spin systems to solve nontrivial combinatorial optimization problems. In particular, we highlight our recent findings on polarization symmetry breaking, offering a new mechanism for all-optical implementation of an Ising machine. Together, these facets illustrate the versatility and transformative potential of ONNs.

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AN ENTANGLEMENT TOOLBOX FOR QUANTUM PHOTONICS

Gerhard REMPE

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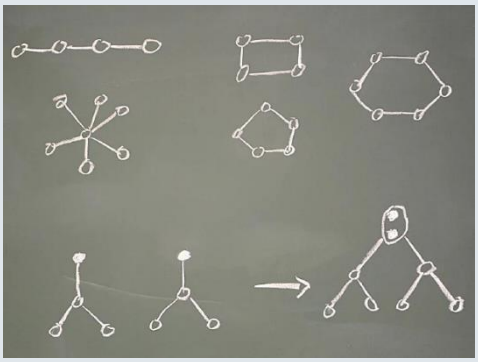
Entanglement is a genuine quantum physical concept that has widely been explored experimentally in few-qubit systems. However, producing customized multi-qubit entanglement is a formidable challenge. The lecture will discuss a powerful approach to generate a zoo of almost arbitrary entanglement topologies described by graphs. These open the door to a multitude of applications in all of quantum photonics and beyond.

Graph states are a class of multipartite entangled states that can be pictured by graphs. They have been proposed as a unique resource for measurement-based quantum information processing. The tools that are available for the manipulation and measurement of light make optical photons ideal for such applications. However, the absence of interaction between photons poses a challenge for entangling photons. The traditional approach relying on spontaneous parametric down- conversion is probabilistic and therefore inefficient. This imposes severe constraints on scalability, even for moderate numbers of qubits.

This limitation can be overcome by using the toolbox of cavity quantum electrodynamics that has been developed at MPQ. By extending previous work with one atom and two photons [1], one-dimensional photonic graph states composed of more than a dozen individually entangled photons have been produced [2]. Next, two addressable atoms have made it possible to merge these states into two-dimensional states with potentially useful topologies such as rings and trees consisting of up to eight physical qubits [3]. Most fascinating, with an improved photon source-to-detection efficiency exceeding 50%, it seems now possible to enter a quantum error correction regime where the logical loss of information can be smaller than the physical loss of information-carrying photons [4].



Pictorial representation of the multi-photon graph states produced at MPQ.

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ORGANIC MOLECULES IN SOLIDS FOR PHOTONICS QUANTUM TECHNOLOGIES

Rocco DUQUENNOY[1], Maja COLAUTTI[1,2], Daniele DE BERNARDIS[1], Elena FANELLA[1], Hugo LEVY-FALK[1], Costanza TONINELLI[1,2]

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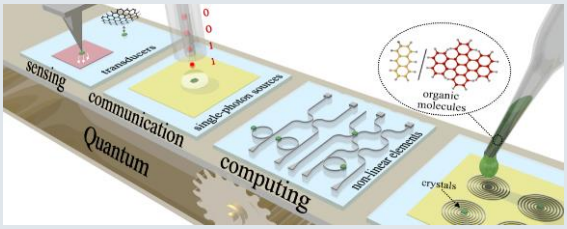
[2] *LENS, Via Nello Carrara 1, Sesto Fiorentino (Fi), Italy*

In this contribution, the generation of quantum states of light from single molecules is discussed, tailored to multiple and diverse applications. We will focus on the use of polycyclic aromatic hydrocarbons (PAH), embedded in host matrices [1]. These molecules, due to their small size and well-defined properties, serve as nanoscopic sensors for pressure, strain, temperature, and various fields. The talk discusses recent advancements in coupling single PAH molecules to photonic structures to enhance and control their interaction with light [2]. Notably, two-photon interference experiments between photons emitted by different molecules on the same chip are presented, addressing a fundamental challenge in solid-state platforms for photonic quantum technologies [3]. The experiment relies on multiple milestones, including addressing several molecules simultaneously as on-demand single-photon sources [4], independently tuning their frequencies optically [5,6], and conducting real-time measurements of two-photon interference [3,7]. Additionally, the presentation explores the use of organic molecules as nanoscopic thermal sensors, enabling semi-invasive local temperature measurements in a temperature range (3 K to 30 K) unattainable by most commercial technologies [8]. These results offer insights into the local phononic environment in complex structures and an unexplored temperature regime. Finally, we will comment on the new prospects of using single molecules as interfaces between spin, optical and mechanical degrees of freedom.



Artistic picture of the different experiments performed with molecules in our Lab.

References

[1] C. Toninelli, I. Gerhardt, A. S. Clark, A. Reserbat-Plantey, S. Götzinger, Z. Ristanović, M. Colautti, P. Lombardi, K. D. Major, I. Deperasińska, W. H. Pernice, F. H. L. Koppens, B. Kozankiewicz, A. Gourdon, V. Sandoghdar, and M. Orrit, Nat. Mat. **20**, 1615-1628 (2021).
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[5] M. Colautti, F. S. Piccioli, Z. Ristanović, P. Lombardi, A. Moradi, S. Adhikari, I. Deperasinska, B. Kozankiewicz, M. Orrit, and C. Toninelli, ACS Nano **14**, 13584–13592 (2020).

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DIPOLAR QUANTUM GASES

Andrea LITVINOV

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Dipolar quantum gases represent a fascinating and rapidly evolving field at the forefront of many-body quantum physics and quantum simulation. These gases, composed of ultracold atoms with strong magnetic moment, exhibit unique and tunable long-range interactions, distinct from the short-range interactions in traditional atomic gases. This lecture provides an overview of key insights and recent developments in the study of dipolar quantum gases and their implications in various experimental setups, such as optical lattices and bulk systems. Moreover, we highlight recent experimental and theoretical advancements in understanding quantum phases, dynamics, and collective phenomena in dipolar gases, ranging from the discovery of a super-solid state of matter to the realization of 'extended' quantum simulators. Overall, the study of dipolar quantum gases continues to inspire innovative research directions and offers promising avenues for exploring new frontiers in quantum science and technology.

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ANALOG PROGRAMMABLE PHOTONIC COMPUTATION AND INFORMATION

José CAPMANY

Universitat Politècnica València, ITEAM Research Institute, Valencia, Spain.

The limitations of digital electronics in handling real-time matrix operations for emerging computational tasks – such as artificial intelligence, drug design, and medical imaging – have prompted renewed interest in analog computing. Programmable Integrated Photonics (PIP) [1-3] has emerged as a promising technology for scalable, low-power, and high-bandwidth analog computation. While prior work has explored PIP implementations of quantum and neuromorphic computing, both approaches face limitations due to misalignments between their mathematical models and the native capabilities of photonic hardware. In this talk we introduce the principles of the recently proposed Analog Programmable-Photonic Computation (APC) paradigm [4,5] – a computation theory explicitly matched to the techno-logical features of PIP and its companion information theory known as Analog Programmable-Photonic Information (API) [6], a mathematical framework that addresses fundamental concepts beyond APC by examining the amount of information that can be generated, computed and recovered in a PIP platform.

The lecture will introduce the basic unit of information or ANBIT, the hardware basic building blocks or gates used to process the information units and the basic generation and detection schemes. It will also cover the impact of errors and noise in the overall performance of these computing approaches by means of its association to the classical block structure of communication systems.

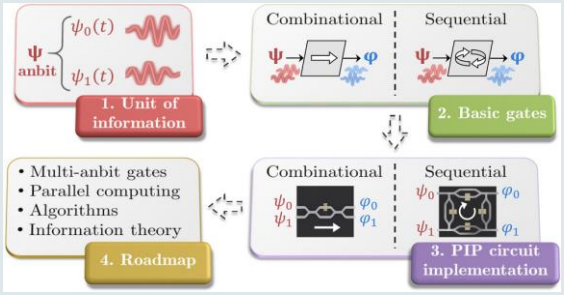

Figure 1. Flowchart of the steps required to construct the new computing model, termed Analog Programmable-Photonic Computation (APC), implementable with programmable integrated photonic (PIP) technology.

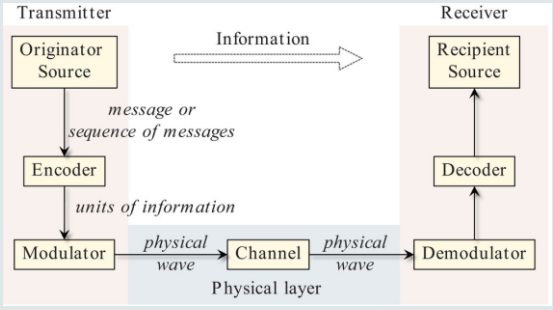

Figure 2. Block diagram of a generic communication system. Any computational architecture (classical or quantum and digital or analog) can be regarded as a communication system composed by a transmitter where information is generated, a channel where information is propagated (e.g., the circuits of an optical chip), and a receiver where information is recovered.

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[1] W. Bogaerts, D. Pérez, J. Capmany, D. A. B. Miller, J. Poon, D. Englund, F. Morichetti, A. Melloni, Programmable photonic circuits, Nature, **586**, 207-215 (2020).

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[6] A. Macho, R. López-March, P. Martínez-Carrasco, F. J. Fraile, J. Capmany, Analog Programmable-Photonic Information, arXiv:2506.21649 (2025).

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QUANTUM SIMULATORS COMBINING ELECTRONS AND PHOTONS

Alejandro GONZÁLEZ-TUDELA

CSIC– Instituto de Física Fundamental, C. de Serrano 113, 28006 Madrid (Spain)

Recent experimental advances in the integration of quantum emitters with nanophotonic structures opens up unprecedented for quantum technologies [1]. In particular, the low dimensionality of the photons enables to obtain longer ranged interactions than with free-space setups that can be harnessed for quantum simulation purposes [2], as well as for improving the figures of merit of non-classical light-generation [3]. Besides, the possibility to engineer topologically non-trivial photonic band structures [4] opens the realization of topological light-matter interfaces [5], opening a path to engineer robust quantum devices based on such effects [6]. In this talk, I will review some of my main contributions to this field.

References

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QUANTUM SIMULATION

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Quantum simulation is one of the most promising and impactful applications of quantum technologies. It aims to address complex many-body problems that are computationally intractable for classical computers by leveraging the power of quantum devices. Quantum simulation finds applications across a wide range of fields, including condensed matter physics, high-energy physics, and quantum optics. There are two primary approaches to performing quantum simulations: analog and digital. Each approach comes with its own set of advantages and challenges. In this presentation, I will introduce the fundamental concepts of quantum simulation, discussing both approaches, the quantum algorithms employed to tackle these complex problems, the effects of imperfections on simulation accuracy, and the practical aspects of various physical implementations.

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QUANTUM COMMUNICATION NETWORKS

Eleni DIAMANTI

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In this lecture, we will discuss the main concepts, critical photonic resources, present efforts and challenges ahead aiming at the deployment of quantum communication networks at various stages of development, with both terrestrial and satellite links, at a global scale. We will also present some examples of applications of such networks spanning from ultra secure communication to advanced cryptographic and communication protocols in distributed architectures.

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DEVICES FOR QUANTUM NETWORKS

Sarah THOMAS

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The future of quantum technologies is likely to be based on quantum networks, which enable secure long-distance quantum communication, and allow smaller quantum processing units to be connected to create powerful quantum computing systems. A key component of future quantum networks is a quantum memory – a device that enables on-demand storage and retrieval of quantum states of light. Quantum memories are necessary for entanglement distribution across large-scale quantum networks and for synchronizing probabilistic operations for photonic quantum computation. I will discuss quantum memories based on light-matter interactions in atomic ensembles. I will present recent work interfacing quantum memories with quantum dot single-photon sources, and novel methods to optimise their efficiency using light-matter interference.

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QUANTUM NODES FOR QUANTUM REPEATERS

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The distribution of entanglement between the nodes of a quantum network will allow new advances e.g. in long distance quantum communication, distributed quantum computing and quantum sensing. The realization of large-scale quantum networks will require quantum repeaters to enable quantum communication over distances much longer than the fiber attenuation length. The nodes of a quantum repeater are matter systems that should efficiently interact with quantum light, allow entanglement with photons (ideally at telecommunication wavelengths) and serve as a quantum memory allowing long-lived, faithful and multiplexed storage of (entangled) quantum bits.

During the first part of the lecture, I will give an introduction on quantum repeaters and give an overview of the platforms that have been proposed and demonstrated for the realization of quantum repeater nodes. The main focus will be on approaches based on collective effects in large ensembles of atoms, implemented both in cold atomic gases and in the solid state with rare-earth doped crystals. These systems are attractive because they allow efficient and long-lived storage of a large number of quantum bits, without the use of high-finesse cavities to enhance the light-matter interaction. The main protocols for storing photonic qubits in these systems will be reviewed.

In the second part of the talk, I will discuss recent experimental progress in the field, including the distribution of light-matter entanglement over large distances in optical fibres, the demonstration of telecom heralded entanglement between remote quantum nodes or the realization of quantum memory arrays.

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ENTANGLEMENT-ENABLED QUANTUM IMAGING

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Entanglement is a key resource in quantum technologies. Without a classical equivalent, it ensures the superior performance of quantum systems over classical ones—provided it plays a non-trivial role in the process. In optical imaging, however, demonstrating the essential role of entanglement is often challenging. Most applications focus on optical correlations derived from entangled states—correlations that can usually be reproduced by classical states—making these correlations the central feature of imaging systems rather than entanglement itself. In our work, we explore imaging scenarios where entanglement plays a critical and non-trivial role. In this presentation, I will review several quantum imaging methods developed in recent years and (try) to clarify the respective roles of correlations and entanglement. And of course there will be pictures of cats!

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MODULAR AND NETWORKED QUANTUM COMPUTING BASED ON SPIN-OPTICAL INTERFACES

Niccolo SOMASCHI[1], and Quandela's team
Helio HUET[2], Dario FIORETTO[1,2], Pascale SENELLART[2]

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In this talk, I will present recent advancements in building quantum computers using photonic technologies. First, I will highlight the features and functionalities of current systems while presenting concrete examples of applications. [1]
I will then present the roadmap and architecture for scaling the platform toward building logical qubits. This approach merges matter and photonic qubits to build a hybrid architecture that offers advantageous error correction thresholds and deployment features. [2]
At the core of the architecture lies a spin-optical interface consisting of a quantum dot single photon emitter that includes a spin. Such devices have been demonstrated to generate linear clusters of entangled photons, or caterpillar states, in a reprogrammable fashion. We have also calculated resource optimization for generating photonic logical qubit states in a fusion-based quantum computing architecture. The order-of-magnitude improvement will be presented and discussed, demonstrating the advantages of this technology for scaling both hybrid and photonic quantum computing approaches. [3]

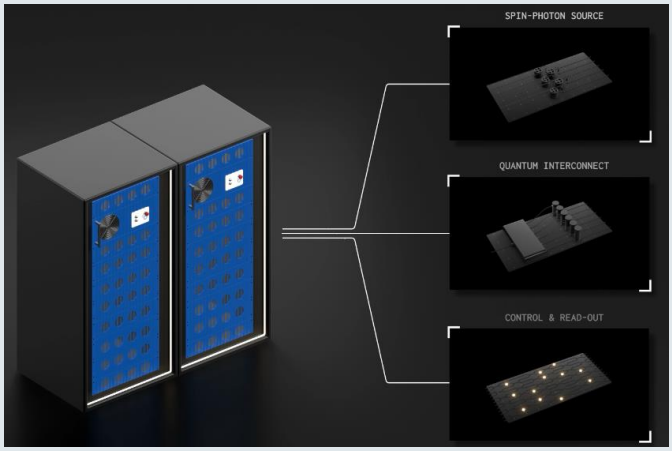

Figure 1. Schematic of the quantum computing server built by integrating quantum opto-electronics modules: spin-photon emitter devices, quantum inter-connects and control and read-out chips based on silicon photonic technologies.

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ANALOG QUANTUM COMPUTERS AND HYBRID DATA CENTERS TO FAST TRACK QUANTUM ADVANTAGE AND UNLOCK GLOBAL ACCESS

Marta PASCUAL ESTARELLAS

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Qilimanjaro[1] is a quantum computing company based in Barcelona, developing full-stack quantum platforms with a focus on analog computation. Established in 2019, the company builds systems based on fluxonium qubits, an alternative superconducting architecture that allows for coherent quantum dynamics with lower overhead than digital gate-based approaches. This design aims to reduce reliance on quantum error correction in the near term.

The hardware is oriented toward applications where analog quantum processing can offer an advantage, particularly in quantum simulation, optimization, and selected machine learning tasks. These are domains where, while fully fault-tolerant digital quantum computers remain out of reach, analog strategies may already provide useful approximations or solution heuristics.

Qilimanjaro supports access to its technology via two pathways:

- A Quantum-as-a-Service (QaaS) platform, providing remote access to hybrid infrastructures combining analog and digital quantum processors with classical HPC.
- On-premise deployments for research institutions and HPC centers, enabling local integration and joint development.

This session will present Qilimanjaro's technical roadmap, the rationale behind its analog-first approach, and use cases demonstrating how such systems can be employed for practical problem solving within current hardware limitations.

Closing of one of our analog quantum computers that will be dedicated to provide cloud access via our QaaS from November 2025.

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MULTIVERSE COMPUTING: QUANTUM AND AI

Roman ORÚS

Multiverse Quantum Computing, Spain

I this talk I will explain the recent advancements that we are carrying at Multiverse concerning quantum and quantum-inspired AI. I will explain how quantum-inspired Tensor Networks can compress AI models such as LLMs up to a 95% without losing almost any accuracy, and which is at the basis of our product CompactifAI. Moreover, I will explain recent projects and products in the context of quantum AI, as well as the history of Multiverse's journey: from a WhatsApp group discussing academic ideas, to the world's top quantum-AI company.

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TOWARDS SECURE NETWORKS USING CV-QKD

Samael SARMIENTO

Luxquanta Technologies SL, Spain

In this talk, we provide an overview of how Continuous Variable Quantum Key Distribution (CV-QKD) can be implemented and integrated into real-world network infrastructures to ensure secure communications.

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Abstracts of contributed talks

REPRODUCIBLE GENERATION OF GREEN-EMITTING COLOR CENTERS IN HBN USING OXYGEN ANNEALING

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The ability to generate quantum emitters with reproducible properties in solid-state matrices is crucial for quantum technologies [1]. Yet when it comes to the emerging material platforms based on 2D materials, most methods yield emitters with a large wavelength spread, including in hexagonal boron nitride (hBN), a 2D insulator that hosts the single-photon emitters (SPEs) with arguably the most advantageous properties [2]. The difficulty of obtaining visible-range SPEs with reproducible wavelength hinders the scalability of their applications to quantum information. Here, we show that a high density of close-to-identical single-photon emitters can be created in commercial hexagonal boron nitride using annealing under oxygen atmosphere. This simple procedure yields uniform in-plane distributions of color centers consistently emitting at 539.35 ± 0.45 nm. We present an extensive characterization of their photophysical properties. At room temperature, we show that the emitters are bright and stable and exhibit a high purity. We also show that at low temperature, the emitters emit predominantly in a narrow zero-phonon line with minimal spectral diffusion. We provide a statistical analysis that demonstrates the high reproducibility of these properties [3]. Altogether, these characteristics make this family of quantum emitters highly appealing for applications to quantum information science.

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FEW-PHOTON SUPER: QUANTUM EMITTER INVERSION VIA TWO OFF-RESONANT PHOTON MODES

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The interaction of a two-level system with a light field is one of the most important models in quantum optics. With the realization of controlled quantum systems these type of models are no longer just of theoretical interest. Here we investigate a Jaynes-Cummings Model with two non-degenerate, off-resonant photon modes coupled to a two-level emitter [1]. In this model we find parameters, for which we can identify multi-photon scattering leading to full inversion of the emitter while transferring off-resonant photons from one mode to another. In this contribution, we give a brief introduction discussing off-resonant excitation in the semiclassical case. After that we introduce the quantized model and discuss where to expect the multi-photon scatterings and how to interpret the results. The case of two off-resonant photons in one mode is considered, showing that the emitter can be inverted by scattering one photon from the occupied mode to the empty mode, with the remaining photon being absorbed by the emitter. This is shown schematically in Figure 1. The results are then generalized to an arbitrary number of photons in both modes. This approach can be seen as a quantized analogue of the off-resonant quantum control scheme known as Swing-UP of quantum EmitteR (SUPER) [2]. Unlike the SUPER scheme, which requires two off-resonant pulses to be present at all times, our model only needs one mode initially occupied and the other mode available to achieve full emitter inversion. Additionally, the behaviour connects to recent measurements of a two-level atom scattering two off-resonant photons simultaneously [3].

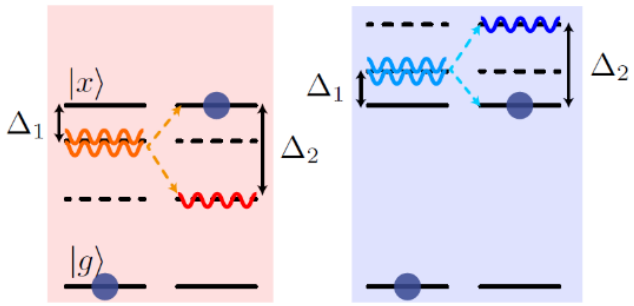

Figure 1. Schematic of the setup. The two-level emitter is coupled to two (red or blue) detuned photon modes. This results in occupation of the two-level system and one photon in the other detuned mode.

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INVERSE-DESIGNED NANOPHOTONIC DEMULTIPLEXER FOR EXCITON ROUTING

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Two-dimensional transition metal dichalcogenides (TMDCs) offer unique excitonic properties and compatibility with heterogeneous integration, making them ideal candidates for light-emitting sources in on-chip photonics. [1, 2] However, leveraging these emissions in compact, wavelength-selective routing structures remains a challenge due to the broadband, low-directionality nature of photoluminescence and the limitations of conventional photonic design strategies. In this work, we demonstrate an inverse-designed wavelength demultiplexer integrated with a WS_2/WSe_2 TMDC heterostructure, enabling on-chip photoluminescence (PL) sorting of exciton emission (Figure 1a). We first validated the demultiplexing functionality using laser excitation at target wavelengths, achieving selective routing with output contrasts exceeding 80% for each channel. Following this, a WS_2/WSe_2 heterostructure was transferred onto the chip. At room temperature, we successfully guided WS_2 and WSe_2 intralayer exciton emissions into their respective outputs (Figure 1b). At cryogenic temperatures (11 K), interlayer exciton emission at 870 nm was also observed and guided, despite its low oscillator strength and directional coupling (Figure 1c). Our work highlights the versatility of inverse design for broadband, multi-functional on-chip photonics and demonstrates the integration of quantum materials in nanophotonic platforms.

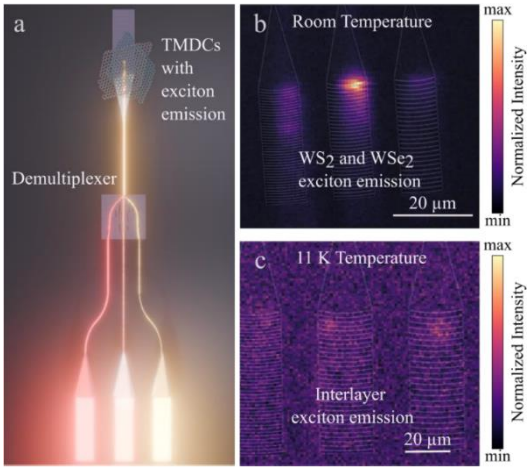

Figure 1. (a) Schematic of the nanophotonic chip based an inverse-design wavelength demultiplexer. Optical measurements demonstrating wavelength de-multiplexing at room temperature (b) and 11 K (c).

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INVERSE DESIGN OF NANOPHOTONIC PLATFORMS FOR ROBUST QUANTUM STATE PREPARATION IN DRIVEN-DISSIPATIVE SYSTEMS

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We explore two distinct yet complementary strategies for the preparation of pure quantum states in nanophotonic environments, leveraging recent advances in computational inverse design [1]. In the first approach, we apply a topology optimization approach to design compact dielectric cavities that enable the steady-state generation of entangled states (such as Bell and W states [2]) between two or three distant quantum emitters driven by continuous-wave lasers [3]. These structures exploit engineered couplings to stabilize high-fidelity entangled states via the driven-dissipative dynamics [4], with emitters separated by several wavelengths and using only moderate-index dielectric materials. In a second scenario, we inverse-design a periodic dielectric structure surrounding a chain of qubits to emulate a dimerized Su-Schrieffer-Heeger (SSH) model [5]. This setup enables precise control over photon-mediated interactions and supports the formation of topologically protected edge states that remain dynamically isolated and resilient against disorder and long-range coupling. Both strategies highlight how nanophotonic design can be harnessed to engineer the quantum dynamics of light–matter systems, offering new pathways toward scalable entanglement generation, quantum state stabilization, and integrated quantum optical technologies.

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SPATIALLY-MULTIPLEXED SOLID-STATE QUANTUM MEMORY

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A long-distance quantum network requires quantum repeaters dispersed between the end nodes and entanglement to be distributed across the network [1]. Successful entanglement events are heralded by detections at intermediate stations placed between the nodes. However, in a sequence of entangling attempts, the repeater nodes must wait for the heralding signal to return from the intermediate station before the next attempt [2]. At intercity distances, the entangling rate consequently may be limited by the time of the photon travel and the classical communication. Quantum repeaters based on rare-earth-doped crystals overcome this limitation, as the atomic frequency comb protocol [3] preparing these memories allows for temporal multiplexing, leading to a linear increase in the entanglement rate with the number of modes [3-4]. The entanglement rate is further increased by combining temporal multiplexing with spatial and frequency multiplexing. In this talk, I will present experiments on quantum storage in a novel spatially multiplexed solid-state memory array. We use acousto-optical deflectors to store and manipulate ten individual memory cells. We characterize the efficiency of the array, determine the crosstalk between the cells, and demonstrate on-demand storage at the single-photon level in 250 spatial-temporal modes. Furthermore, we encode qubits in the time and path degrees-of-freedom and store the qubits. The fidelities of the retrieved qubits are assessed via quantum tomography and violate the classical bound for all memory cells. In near future, we will entangle each cell with a telecom photon traveling 50km of fiber and demonstrate an increase of the entanglement rate due to the multiplexing.

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VERSATILE ENTANGLEMENT SYNTHESIZER FOR THE GENERATION OF HIGH-DIMENSIONAL QUANTUM STATES

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Quantum information protocols rely on diverse forms of entanglement—from simple bipartite pairs to high-dimensional, multipartite correlations—making flexible state generation pivotal [1]. Here, we implement a dynamically programmable system based on a single squeezed vacuum source and a time-bin loop architecture [2]. This platform exceeds prior capabilities by creating highly tunable multi-mode entangled states by addressing the individual states in the time domain. Precise and active phase stabilization allows for the generation of one-dimensional cluster states that span, in principle over thousands of modes. The resource-efficient time-bin framework supports the generation of complex entangled states for a broad range of applications—including sensing, communication, and error-corrected computing—while showcasing the advancement in quantum information processing with fast, low-loss, highly tunable devices as a near-future alternative for spatial-mode implementations in waveguide circuits [3].

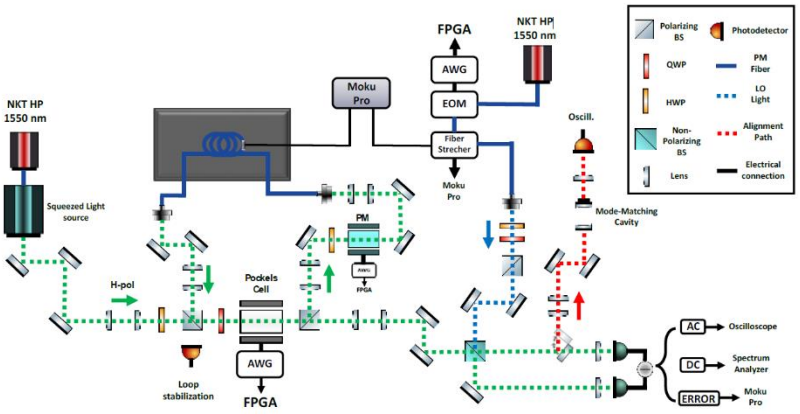

Figure 1. Experimental implementation for the realization of higher dimensional entangled state. The system utilizes squeezed state of light time-bin modes as quantum resource. The generation of different entangled states can be realized by interfering multiple modes while addressing individually the transformations of each mode.

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QUANTUM RESERVOIR COMPUTING BASED ON OPTICAL MEMRISTORS

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Quantum neuromorphic computing presents a promising approach to implementing efficient physical neural networks; however, practical hardware implementations remain a significant challenge. Classical memristors, resistors with memory, have been widely studied as potential neuromorphic elements [1]. Here, we present a photonic reservoir computing framework inspired by the photonic experimental quantum memristor design by Spagnolo et al. [2]. In particular, we modify the original design to enhance memory and nonlinear dynamics by incorporating an additional optical mode and using dual rail encoding to feedback previous outputs. This introduces injection memory, complementing the reflectivity memory of the original design. This proposal targets time-series processing in machine learning, leveraging integrated photonic circuits for neuromorphic computing. These circuits offer a compact footprint, low power use, and ultrafast signal processing, making them a strong alternative to electronic architectures. The entire neuronal network is constructed through spatial multiplexing, assigning each computational element a unique random mask and distinct dynamics. These configurations allow diverse memory perspectives, boosting expressivity. The resulting framework, studied through numerical simulations, enhances short-term memory and achieves higher accuracy on nonlinear tasks, such as NARMA, Lorenz forecasting, and MNIST classification, underscoring its potential for quantum reservoir computing.

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ON-CHIP PHOTONIC AND SUPERCONDUCTING CIRCUITS FOR ERBIUM^{3+} ION PROPERTY ANALYSIS

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Erbium (Er^{3+}) ion-doped yttrium orthosilicate (YSO) crystals, combined with silicon waveguides, have demonstrated significant potential for on-chip quantum memories [1]. Other host materials, such as yttrium vanadate (YVO) and calcium tungstate (CaWO), also show promise as efficient platforms for quantum memory applications [2] and microwave-to-optical transduction [3,4]. In this contribution, we present innovative fabrication techniques designed to streamline the characterization of various on-chip coupling strategies for Er^{3+} ions across different host materials. A stamping transfer process [5] for silicon waveguides allows rapid prototyping using standard silicon wafers. Utilizing a PDMS stamp with a precision stacker, commonly used for 2D material transfer, we efficiently transfer silicon waveguide structures. Combined with inverse design grating couplers [6], this method enables fast characterization of different platforms. These grating couplers, designed for simultaneous transfer with waveguides, are arranged in arrays held together by a transfer structure. Additionally, we introduce a macroscopic microwave split-ring resonator cavity, fabricated on a printed circuit board, for Er^{3+} spin control. This cavity, optimized for a second-harmonic resonance frequency of 5.236 GHz with a full-width half-maximum of 24.08 MHz, achieves a measured quality factor of 217. The design allows for rapid modifications to accommodate different host materials and manage restricted cryostat space, as well as varying sample dimensions and orientations. The integration of on-chip photonics enables the investigation of quantum memory applications using photonic crystal cavities to enhance memory efficiency. Combined with on-chip superconducting microwave resonator, we can explore spin control and transduction [7], advancing the capabilities for quantum technologies.

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SPATIALLY RESOLVED PHOTON STATISTICS OF GENERAL NANOPHOTONIC SYSTEMS

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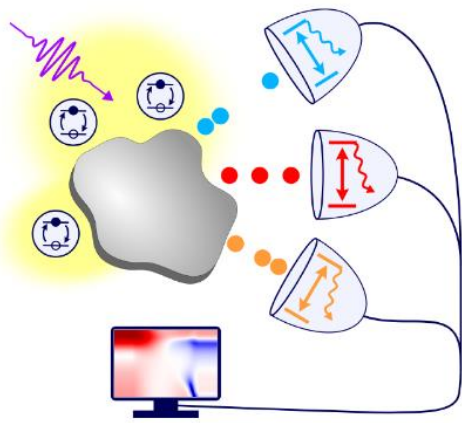
Understanding the statistical behaviour of photons emitted by a quantum system is pivotal for advancements in quantum technologies, particularly in the field of quantum communication networks where sources generating light with demanded statistics play an important role. While experimental measurement of photon correlations has become routine in laboratories, theoretical access to these quantities for the light generated in complex nanophotonic setups still remains a significant challenge. Current methods are limited to specific simplified cases, lacking generality. In this study, we present a novel method that provides access to spatially resolved photonic statistics for arbitrary nanophotonic setups. Within the Macroscopic QED framework, we develop a practical tool to calculate electric field correlations for complex quantum systems by including lossy two-level systems that act as the field detectors within the setup [1]. In order to make computational part feasible we employ a recently developed method for few-mode quantization with several emitters to account correctly for light propagation to detectors [2, 3]. We demonstrate the effectiveness and robustness of the proposed technique by studying the photon correlations of one and two emitters in close proximity to a plasmonic nanoparticle. The simulations show that even in these relatively simple configurations, the light statistics exhibit a strong angular dependence. These results highlight the importance of going beyond conventional quantum-optical approaches to fully capture the analysed physical effects and enable the study of the quantum light generation in realistic nanophotonic devices



Sketch of the method.

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ELECTRIC-FIELD CONTROL OF PHOTON INDISTINGUISHABILITY IN CASCADED DECAYS IN QUANTUM DOTS

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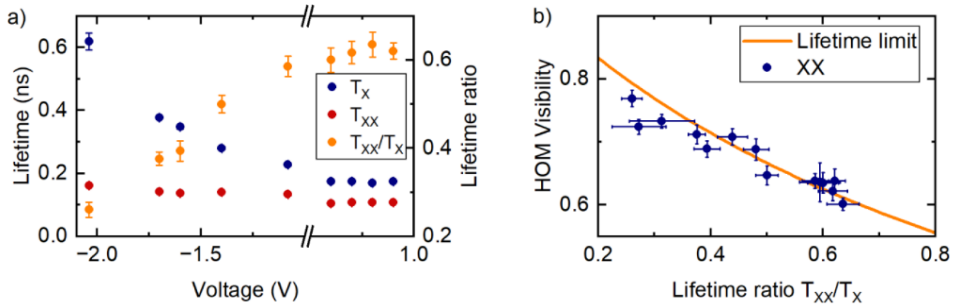
Many quantum technology applications require tailored quantum light sources that satisfy stringent criteria on the emission properties. Epitaxial semiconductor quantum dots operated at cryogenic temperatures (5 K) have emerged as promising sources of single photons with high purity, and near-unity indistinguishability. Additionally, the biexciton-exciton cascade allows the direct generation of highly entangled photon pairs, although the indistinguishability of cascaded photons is fundamentally limited by the lifetime ratio of the involved states [1]. We show that this ratio can be widely tuned via an applied electric field [2] (Fig. 1a) and demonstrate a corresponding increase in photon indistinguishability through Hong-Ou-Mandel (HOM) interference measurements, in agreement with theoretical predictions (Fig. 1b). These findings help the development of quantum light sources combining all key properties for applications in quantum technology.



a): Biexciton (XX) and exciton (X) lifetimes as a function of the voltage. For decreasing voltage (increas-ing electrical field), the relative increase of TXX is much lower than that of TX, resulting in a decrease of the life-time ratio. b) HOM visibility of the XX and theoretical limit as a function of lifetime ratio TXX/TX.

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Abstracts of posters

QUANTUM STATE PREPARATION AND READOUT WITH MODULATED ELECTRONS

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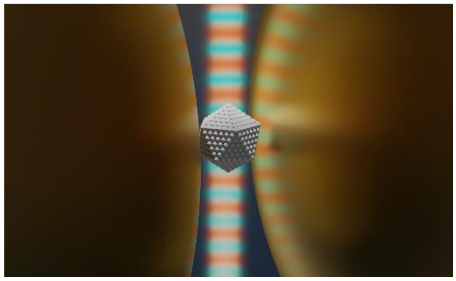
Recent advances in free-electron wavefunction control have opened the door to free-electron quantum optics, where free electrons serve as quantum-optical tools. Using macroscopic quantum electrodynamics, we develop a model Hamiltonian describing their interaction with arbitrary fermionic and bosonic quantum targets [1]. This work explores the coherent interaction between modulated free electron wavepackets and single quantum emitters, unveiling new possibilities for quantum state manipulation and readout. We further demonstrate how free electrons probe and modify polaritonic excitations in hybrid light–matter systems. These findings establish free electrons as both spectroscopic tools and active quantum resources, with applications in quantum information and ultrafast electron microscopy [2].



Artist's rendering of the interaction between a modulated free electron and a polaritonic target composed of a quantum dot embedded in the gap of a metallic dimer.

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DETERMINISTIC SINGLE-ION IMPLANTATION OF Er INTO THIN FILM LITHIUM NIOBATE

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Lithium niobate on insulator (LNOI) is an ideal platform for photonic integrated circuits (PICs) due to its strong electro-optic and acousto-optic properties, wide transparency window, and significant second-order nonlinearities [1]. Rare-earth ions (REIs), on the other hand, are well known for their stable optical transitions, high fluorescence quantum efficiencies, long population lifetimes, and narrow homogeneous linewidths [2]. Additionally, REIs have been widely used in quantum information applications due to the weak coupling of their 4f electrons to the environment [3].

Q-one single ion implantation equipment [4].

Incorporating REIs into LNOI is of great interest in scalable PICs, enhancing the potential of LNOI with added functionalities enabled by the REIs. Erbium ions, one of the REIs, can be incorporated into LNOI via ion implantation and implemented at telecom wavelengths (~1550 nm). In collaboration with Ionoptika Limited, we have customized a single-ion implantation system called Q-One, capable of operating with an acceleration voltage of up to 40 kV. Using a liquid metal alloy ion source (LMAIS), the Q-One system can achieve a minimum spot size of 20 nm [4]. However, the fabrication of large-scale arrays using ion implantation has two challenges: generating a single-ion implantation signal from the target substrate and achieving high spatial precision in single-ion placement [5]. The first challenge is addressed by measuring the detector efficiency of the QOne system. Results show that single Er ion implantation into LNOI achieves ~85% efficiency in detecting secondary electron emission. The Q-One single-ion implanter, with its high-resolution mass-filtered focused ion beam, nanometer-precision stage, and flexible ion source options, holds significant promise for deterministic ion implantation—crucial for scalable quantum technologies based on REIs.

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SPATIAL MODE DEMULTIPLEXING FOR QUANTUM SUPER-RESOLUTION IMAGING

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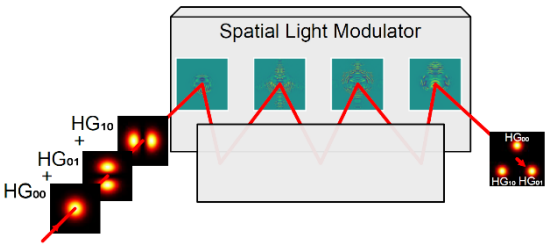
The resolution of imaging systems involving a camera and lens system, referred to as direct imaging, is limited by diffraction. In fluorescence microscopy, techniques like stimulated emission depletion can be used to improve beyond the diffraction limit [1]. However, as they require interaction with the observed object, which may damage the sample, they are only applicable in certain cases. For some objects, e.g. in astronomy, active techniques are entirely impossible. Hence, there is a need for passive super-resolution imaging methods. Analysing the task of estimating the distance between two point-sources in the framework of quantum parameter estimation shows that the ultimate measurement precision is independent of the source separation [2]. The corresponding optimal measurement consists out of intensity measurements in a spatial mode basis. Such a demultiplexing measurement can be practically implemented through multiplane light conversion (MPLC) [3].

In these practical implementations, the presence of noise and crosstalk between measurement modes limits the estimation performance. Nevertheless, it has been shown that an improvement beyond direct imaging is always possible [4]. Our implementation of MPLC uses multiple bounces on a spatial light modulator (SLM). At each spot a phase mask is displayed on the SLM that combined with free space propagation applies a unitary transformation to the incoming light [4]. In this way, the demultiplexing basis can be adapted to the input scenario by changing the phase masks.



Visualization of the spatial demultiplexing process using multi-plane light conversion. Three spatially collocated Hermite-Gaussian (HG) modes are demultiplexed into three spots in the HG00-mode.

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CASCADED METASURFACES FOR MULTI-PORT BEAMSPLITTING

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Beam splitters are essential components in many optical systems, typically realized as 2×2 elements that map up to two input modes onto two output modes. To achieve higher-dimensional operations, multiple 2×2 beam splitters are often cascaded, resulting in bulky setups with significant optical losses [1]. This is particularly detrimental in quantum optics applications, where minimizing loss is critical. While photonic integrated circuits offer more compact alternatives, they often face challenges in scalability and flexibility [2]. Flat optics, and particularly metasurfaces, offer a promising solution by enabling arbitrary wavefront shaping in a compact form factor. Recent demonstrations of metasurface-based beam splitters have focused primarily on single-input, multiple-output configurations [3]. However, more advanced applications such as quantum interference require multi-input operation. In this work, we present a cascaded metasurface architecture that functions as a 4-input, 7output beam splitter with reconfigurable splitting ratios (Fig 1). We characterize its performance using a CCD sensor to extract the intensity distribution across output ports. Furthermore, we demonstrate its suitability for quantum applications by interfacing it with a semiconductor quantum dot, observing single-photon multi-port interference and higher-order photon correlations.

Experimental setup for characterization of multi in-output metasurface. The input beam can be easily exchanged for any type of light source.

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GENERATION OF QUANTUM-ENTANGLED LIGHT IN SELF-PULSING OPTICAL CAVITIES

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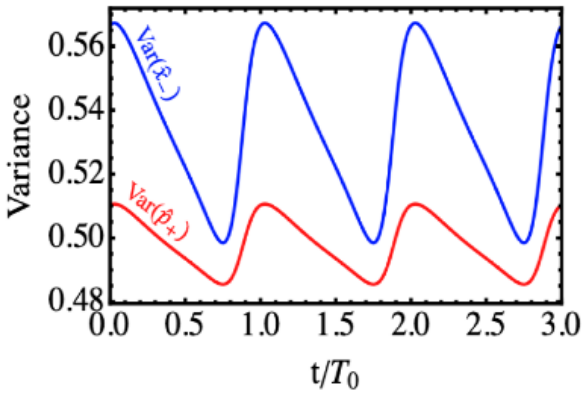
We characterize the quantum correlations of light generated inside an actively phase-locked type II Optical Parametric Oscillator (OPO). This system consists of a second order nonlinear crystal within an optical cavity. When the crystal is pumped with a laser at frequency $2\omega_0$, it can generate two down-converted modes with orthogonal polarizations and resonating inside the cavity at frequency ω_s (signal) and ω_i (idler) such as $\omega_s + \omega_i \approx 2\omega_0$. When we also inject light at frequency ω_0, it is found [1] that pulsed stable emission in the form of limit cycles is achieved for a wide range of parameters. These solutions are characterized by a periodic modulation of the light's intensity and phase. While quantum properties of these cavities are well studied in the stationary regime [1], they have not been characterized yet in this pulsating regime. In this work we find that there exists a high level of entanglement between the signal and idler modes, by proving that the time-dependent quadratures $\hat{x}_- = (\hat{x}_s\,\phi(t) - \hat{x}_i\,\phi(t))/\sqrt{2}$ and $p_+ = (p_s\,\phi(t) + p_i\,\phi(t))/\sqrt{2}$ are squeezed (Figure 1). Here, $\phi(t)$ is a periodic function that acts as a time-dependent rotation angle in the phase space defined the position and momentum of the modes. We provide analytical results within a linearized theory of quantum fluctuations [2,3], which are confirmed by numerical simulations of the stochastic phase-space equations that model the quantum dynamics exactly. The next step will consist in proving that the light coming out of the cavity also shows strong entanglement, leading to a practical source of quantum correlated light with a nontrivial temporal profile. From a fundamental point of view, this is interesting as an example of quantum mechanical effects derived from spontaneous time-translationally symmetry breaking.



Variance of the quadratures $\hat{p}_+$ and $\hat{x}_-$ (defined in the text) over 3 periods T_0. Values below 1 signal squeezing below that of coherent light, and hence entanglement between signal and idler modes.

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QUANTUM TELEPORTATION WITH DISSIMILAR QUANTUM DOTS OVER A HYBRID QUANTUM NETWORK

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Photonic quantum information processing in metropolitan quantum networks lays the foundation for cloud quantum computing [1, 2], secure communication [3, 4], and the realization of a global quantum internet [5, 6]. This paradigm shift requires on-demand and high-rate generation of flying qubits and their quantum state teleportation over long distances [7]. Despite the last decade has witnessed an impressive progress in the performances of deterministic photon sources [8–11], the exploitation of distinct quantum emitters to implement all-photonic quantum teleportation among distant parties has remained elusive. Here, we overcome this challenge by using dissimilar quantum dots whose electronic and optical properties are engineered by light-matter interaction [12], multi-axial strain [13] and magnetic fields [14] so as to make them suitable for the teleportation of polarization qubits. This is demonstrated in a hybrid quantum network harnessing both fiber connections and a 270 m free-space optical link connecting two buildings of the University campus in the center of Rome. The protocol exploits GPS-assisted synchronization, ultra-fast single photon detectors as well as stabilization systems that compensate for atmospheric turbulence. The achieved teleportation state fidelity reaches up to 82 ± 1%, above the classical limit by more than 10 standard deviations. Our field demonstration of all-photonic quantum teleportation opens a new route to implement solid-state based quantum relays and builds the foundation for practical quantum networks.

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GEOMETRIC ANTIBUNCHING AND QUANTUM NONLINEARITIES IN ATOMIC ENSEMBLES

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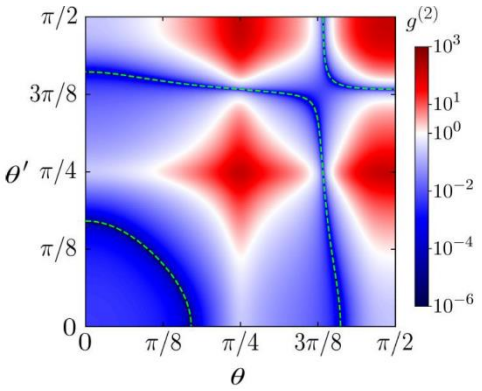
Although the study of temporal photon statistics has been a cornerstone since the beginning of the field of quantum optics, the second-order spatial coherence has been greatly overlooked. In this work [1], we investigate the directional characteristics of photon statistics in dimers of quantum emitters. For their analysis, we construct a two-point second-order correlation function that allows us to find a new mechanism for photon anticorrelation, termed as geometric antibunching. This phenomenon is completely agnostic to the quantum state of the emitters and emerges from quantum interference effects due to the indistinguishability of different two-photon optical pathways. We explore its occurrence in emitters placed in the vicinity of a flat substrate and a nanosphere, demonstrating its tunability through the different material and geometric parameters of these structures.

Motivated by the insights obtained from the dimer case, we consider the limit of an infinite array. In this new work [2], we theoretically investigate the optical response of a periodic lattice of quantum emitters coherently driven by a plane wave. We demonstrate that, contrary to the case of a lattice formed by bosonic (classical) resonators, a coherent, resonant plane wave driving excites a continuum of Bloch states with a parallel wave vector different than the incident one, even beyond the light cone.

Consequently, in close relationship with the phenomenon of resonance fluorescence, the lattice emission into the far-field is dominated by a background of photons at any frequency and wavevector for strong driving.



Maps of directional correlations, $g^{(2)}(\theta, \theta')$, for a vertically oriented QE dimer placed above a perfect mirror. The polar angles θ, θ' represent the directions in the far-field where light is detected. The laser driving is set to target the antisymmetric state of the QE dimer. Green dashed curves indicate geometric antibunching zeros, where $g^{(2)}(\theta, \theta')$ vanishes independently of the quantum state of the emitters.

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UNLOCKING MULTIPHOTON EMISSION FROM A SINGLE-PHOTON SOURCE THROUGH MEAN-FIELD ENGINEERING

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For single-photon emitters—a cornerstone in quantum optics, powering advancements from quantum technologies—multiphoton events are traditionally viewed as accidental and undesirable. Efforts to achieve purer single-photon streams by strongly suppressing multiphotons have received significant attention. Our study challenges this paradigm by demonstrating that multiphotons in the resonance fluorescence of a two-level system (TLS) govern the underlying physics of shaping the finally observed outcome in quantum mechanics, despite their small quantitative contribution. Specifically, we investigate the resonance fluorescence of a TLS—a neutral exciton transition in a single InGaAs quantum dot—under weak coherent driving. In this regime, the observation of multiphotons is hindered by quantum interferences between a mean field and multiphoton fluctuations in its well-established single-photon emission. By employing a precise homodyne technique, we seize the control over these quantum interferences thereby unlocking and amplifying multiphotons from the stream of single photons as well as realizing their individual suppression [1]. Experimentally, we observe that antibunching ($g^{(3)}(0) < g^{(2)}(0) < 1$) of the undisrupted single-photon emission turns into superbunching ($g^{(3)}(0) > g^{(2)}(0) > 1$) in multiphoton correlations when the emission is reduced to its quantum fluctuations. By precisely admixing the classical and quantum fields, we achieve suppression of specific photon numbers, such as two-photon suppression ($g^{(2)}(0) < 1 < g^{(3)}(0)$) and three-photon suppression, ($g^{(3)}(0) < g^{(2)}(0) \lessapprox 1$), revealing how the multiphoton coincidences behave independently from each other. Our demonstration highlights that, counterintuitively, the quantitatively weak multiphoton fluctuations always play a significant qualitative role in the system. The mean-field engineering can serve as a universal tool for harnessing multiphoton physics, unlocking multiphoton emission in coherently driven quantum systems, and enabling the generation of non-classical light far beyond single-photon sources.

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COHERENT SIV CENTER IN DIAMOND NANOPHOTONIC WAVEGUIDE FOR QUANTUM INFORMATION

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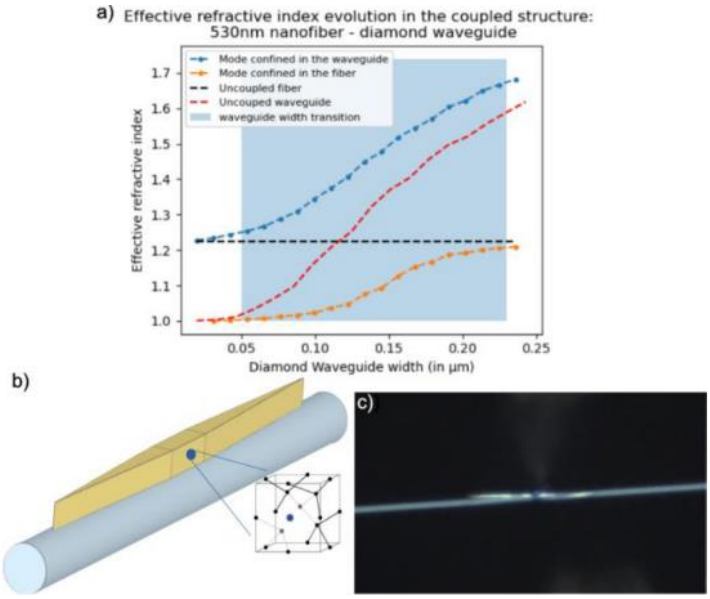
Single photon sources of different types have been widely studied in the past years for quantum information. However, collecting efficiently their single photon emission remains a challenge. Solid-state single photon sources can be compact compared to traditional atomic systems, and can be integrated in photonic chips. Our work focuses on the optical coupling of a diamond nanowaveguide with embedded group IV-color centers and specifically silicon vacancy (SiV) centers, to a nanofiber (cf. figure 1). Optical nanofibers, with their sub-wavelength diameters, can interact with their surrounding environment through an evanescent field at their surface. We can therefore perform an adiabatic transfer of the single photons with tapers on both ends of the diamond nanowaveguide, to ensure a smooth transition between the two eigenstates, without incurring energy losses through change in the eigenvalue (cf. fig 1 a))[1][2]. We developed a pick-and-place setup and technique for the deposition of the waveguide onto the nanofiber (cf. fig 1 c)). As at low temperatures, the quality and directionality of emitted photons are significantly improved, we will proceed with the integration of the platform into a cryostat at 3K. Future studies will consider other shapes of waveguides [3] as well as focusing on exploring interactions such as giant nonlinearities between single photons and quantum emitters [4] to develop a functional optical control switch for single-photons.



a), b) Coupled modes in the nanowaveguide-nanofiber structure from the center to the end of the tapered part c) experimental deposition under optical microscope

Single photon sources of different types have been widely studied in the past years for quantum information. However, collecting efficiently their single photon emission remains a challenge. Solid-state single photon sources can be compact compared to traditional atomic systems, and can be integrated in photonic chips. Our work focuses on the optical coupling of a diamond nanowaveguide with embedded group IV-color centers and specifically silicon vacancy (SiV) centers, to a nanofiber (cf. figure 1). Optical nanofibers, with their sub-wavelength diameters, can interact with their surrounding environment through an evanescent field at their surface. We can therefore perform an adiabatic transfer of the single photons with tapers on both ends of the diamond nanowaveguide, to ensure a smooth transition between the two eigenstates, without incurring energy losses through change in the eigenvalue (cf. fig 1 a))[1][2]. We developed a pick-and-place setup and technique for the deposition of the waveguide onto the nanofiber (cf. fig 1 c)). As at low temperatures, the quality and directionality of emitted photons are significantly improved, we will proceed with the

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NEAR FOURIER-TRANSFORM LIMITED BLINKING FREE QUANTUM DOTS

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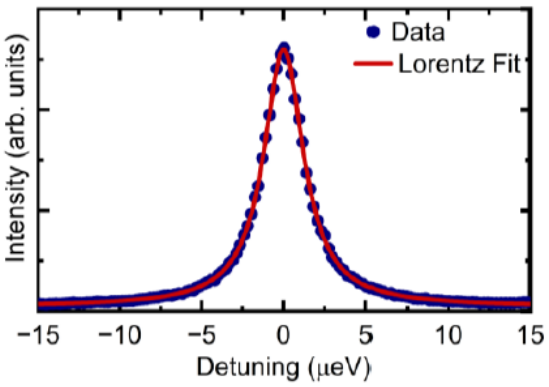
High single-photon purity and high indistinguishability are two of the most crucial properties of photonic qubits for quantum technologies. In particular for multi-source applications the two-photon interference strongly depends on the proximity to the Fourier transform (FT) limited linewidth, indicating maximum coherence of the emitted photons. This key performance indicator can be calculated by performing linewidth and lifetime measurements. Unfortunately, self-organized grown QDs still suffer from charge instabilities and blinking deteriorating these properties. Here we present semiconductor QD transitions emitting photons close to the FT limit and with low blinking. By embedding aluminium droplet-etched QDs, known for their already promising properties, in a p-i-n diode [3] and a weak cavity, we can apply a charge-stabilizing electric field to them. This allows us to reach the FT limit up to a factor of 1.1 and receive a HOM visibility of about 92.8% with an almost blinking-free emission. Droplet-etched QDs with their low quantum dot density and large uniformity in combination with the integration in a diode therefore proves to be a possible foundation for the emission of high-quality single-photons and opens the door to more complex multi-source experiments.



Linewidth Scan of the X- transition of a droplet-etched GaAs/AlGaAs quantum dot in the p-i-n diode.

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ADVANCES IN QUANTUM LIGHT GENERATION FOR QUANTUM NETWORKING

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Recent progress in the generation and precise control of qubits, whether photonic or embedded in the solid-state, has been one of the main drivers of innovation in quantum information science. This poster reviews contributions in the fields of quantum light generation in the solid-state and implementations of quantum information, ultimately striving toward scalable quantum networks.
First, we show recent advances in the fabrication of deterministic quantum dot devices based on hybrid circular Bragg gratings (hCBG) [1] (see Fig. 1), enabling high Purcell enhancements $F_P > 25$ resulting in ultra-low lifetimes <30 ps and a high degree of photon-indistinguishability at temperatures of up to 45 K. These fiber coupled single-photon sources also exhibit excellent quantum optical properties ($g^{(2)}(0) < 1\%$ and >80% photon-indistinguishability). Moreover, we demonstrate the generation of fiber-coupled indistinguishable photons at clock-rates of the excitation laser of up to 1.28 GHz enabled by the strong Purcell enhancement [2]. Second, we employ these sources in experiments demonstrating a first quantum cryptographic primitive beyond QKD [3]. More specifically, we experimentally implement a quantum strong coin flipping protocol and demonstrate an advantage compared to both, classical realizations and implementations using faint laser pulses. We achieve this by employing a fast polarization-state encoding, enabling a quantum bit error ratio below 3%. Lastly, we report recent progress in establishing a quantum local area network at TU Berlin employing an actively stabilized free-space optical link with an effective length of 400 m and an end-to-end transmission of >70%.

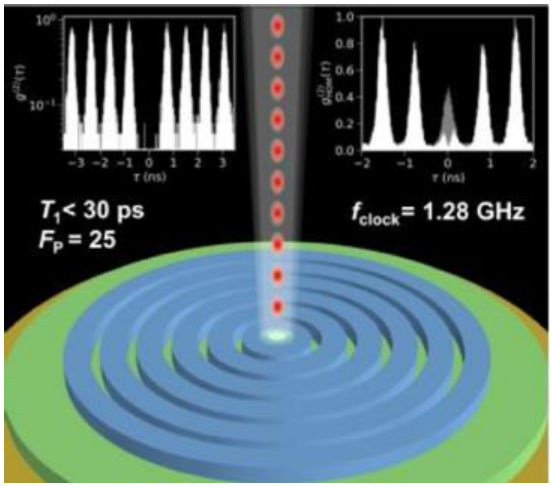

Illustration of a high-Purcell microcavity featuring quantum dot emission lifetimes <30 ps enabling excellent quantum optical performance and clock-rates in the GHz regime [1].

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NEAR-IDEAL MODE-MATCHED EMISSION FROM QUANTUM DOT MICROPILLAR INTO SINGLE MODE FIBRE WITH INTEGRATED ASPHERIC MICROLENS

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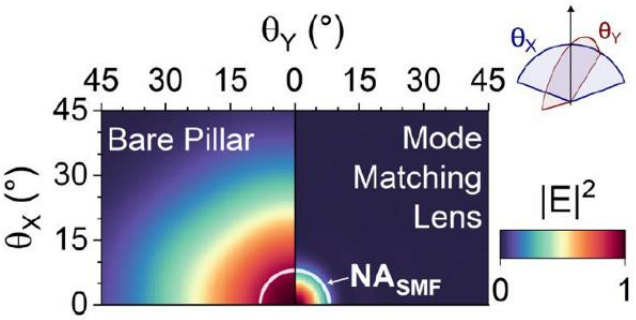
Quantum dots in micropillars are one of the most promising options for a bright, deterministic single photon source. While highly efficient devices (>95%) have been designed, there remains a significant bottleneck that impacts the overall system efficiency: the large numerical aperture of the output mode. This leads to inefficient coupling of emitted photons into single-mode fibre, thus limiting practical integration into quantum computing and communication architectures. Through our group simulations, we find that the addition of a well-designed aspheric SiO2 microlens can decrease the mode-matching losses to a SMF from 83.1% to <0.1(0.1)%. Figure 1 shows the drastic effect of the microlens on matching the output far-field emission to that of a SMF – the white semicircle. This can result in a single photon source design with 96.4(0.1)% end-to-end efficiency, [1] paving the way for scalable photonic quantum technologies. The lens radius ~5.7µm and height ~10µm makes this device on the edge of fabrication tolerances for 3D structures with techniques such as two-photon polymerization (TPP) and focused ion beam (FIB) as options. [2, 3] In my project, I am using TPP to fabricate an aspheric SiO2 microlens on top of a quantum dot (QD) micropillar, not yet done before. As part of this work, I have simulated many types of fabrication errors – lens concentricity to pillar, lens height, machine step size impacting lens smoothness – and the lens performs excellently (>90% of maximum effectiveness) up to within tolerances of TPP. I am currently working on printing these microlenses onto a QD sample, having successfully printed on test substrates. After realizing the microlens-on-pillar, I will work on the plug-and-play aspect of this single-photon source and find a scalable and effective way to package it.



The far-field intensity of the micropillar emission without and with the aspheric microlens. The far-field NA of a SMF has been shown in a white semicircle.

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EXPERIMENTAL MULTI-PARAMETER ESTIMATION OF THE STATE OF TWO INTERFERING PHOTONIC QUBITS

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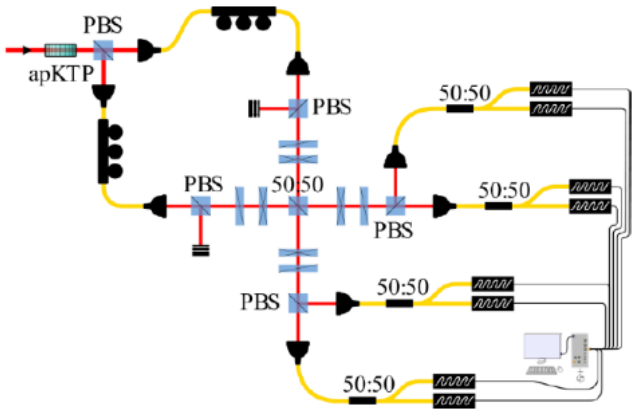
Quantum metrology is one of the most promising applications of quantum technology, such as in atomic clocks, gravitational wave detection and magnetometry. Much of this work has been dedicated to single-parameter estimation, where it is proven that in the many-sample limit, an unknown parameter may be estimated to the maximum sensitivity achievable in nature, the Quantum Cramér-Rao bound (QCRB), under a suitable measurement scheme. However, realistic sensing schemes often require the simultaneous estimation of multiple parameters and in this case, saturation of the bound is not guaranteed and experimental implementations remain largely unexplored. [1–3]

We present an experimental implementation of the protocol introduced by Maggio et al. [4], achieving high-precision characterization of two qubits. By employing polarization-resolved two-photon interference at a beam splitter, we approach the ultimate QCRB for jointly estimating the polar angle and the relative phase difference between the two qubits. We report measurements across the multiparameter range, demonstrating high-precision estimation even with limited sample size (~200 two-photon events). Measured variances in the estimators closely match theoretical predictions, confirming the protocol's efficacy and practicality. This work demonstrates the feasibility of photonic platforms to achieve the highest possible precision in multi-parameter estimation, using realistic experimental resources.



Experimental setup for quantum photonic multi-parameter estimation, using a novel polarization resolving interferometer.

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GaAs QUANTUM DOTS IN AN OPEN MICROCAVITY

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In recent years, GaAs quantum dots were established as quantum emitters with exceptional photonic coherence [1] and hosts of coherent electronic spins [2]. The ability to control the spin in an all-optical manner as well as the intrinsically low strain allow for efficient cooling of the nuclear spin bath. This way, the electronic spin coherence time can be greatly enhanced [3]. Together with the high photon indistinguishability, this makes GaAs quantum dots a promising platform for deterministic spin-photon interfaces and hence future photonic quantum technologies.
However, in order to obtain high photon extraction efficiencies required by technological applications, engineering of the quantum dot's photonic environment is needed. A successful concept in this regard is an open, tunable microcavity [4]. This approach allows for technologically relevant end-to-end efficiencies while being compatible with spin control and cooling of nuclear spins [5]. The integration of GaAs quantum dots into such a microcavity requires the design and growth of a semiconductor heterostructure and the fabrication of top mirrors. A GaAs quantum dot in an open microcavity will be an enabling device for both fundamental research as well as technological applications.

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MONITORED GENERATION OF INDIVIDUAL QUANTUM EMITTERS IN HBN USING ELECTRON BEAM IRRADIATION

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Color centers act as single photon emitters [1] and represent a major interest in quantum information science. We have recently demonstrated [2] a new family of single photon emitters in hBN called B-centers, which can be locally activated using an electron beam in a scanning electron microscope (SEM) [3]. However, several color centers are usually generated instead of just one emitter. In this work, we developed an experimental system which creates individual B-centers and investigate its generation mechanism from preexisting UV-emitting defects in the crystal.

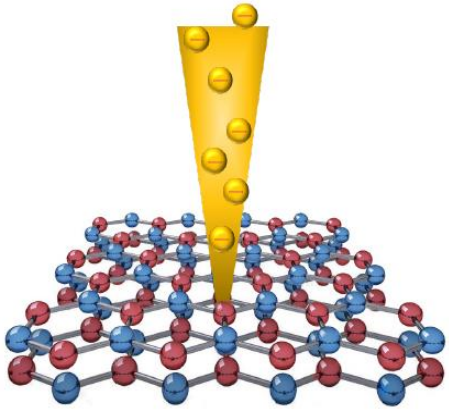

Figure 1 Representation of electron

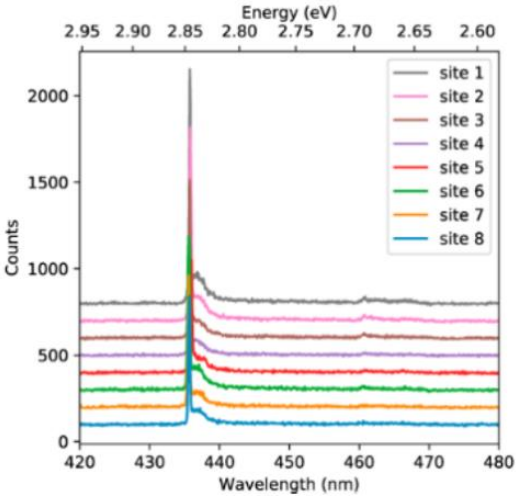

Figure 2 Emission spectra of several B centers at cryogenic temperatures, revealing similar emission lines [2]

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SPATIAL COHERENCE OF EXTENDED IX ENSEMBLES IN $MoSe_2/WSe_2$ HETEROSTRUCTURES

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In this thesis, we focus on the experimental study of spatial coherence of interlayer exciton ensembles in $MoSe_2/WSe_2$ heterostructures, by means of point-inversion Michelson Morley interferometry. The detection of spatially resolved PL images revealed an extension of the PL signal, which exceeds the point spread function (PSF) of the optical circuitry [1]. Our findings show that for the lowest excitation power P_{laser} = 200 nW and at a cryogenic temperature of T = 1.7 K, the measured spatial coherence length is well above the PSF, reaching a value of x_c = (1.6 ± 0.3) µm [1]. Intriguingly, for the same excitation power of P_{laser} = 200 nW, the excitonic photoluminescence is comparable to the lateral expansion of the exciton ensembles [1]. Furthermore, for increasing powers the spatial coherence of the excitonic system decreases to the PSF limit, suggesting enhanced dipole-dipole and exciton-exciton interactions [1, 2]. Time-resolved measurements were introduced to exclude local heating or possible laser-induced coherence effects. As a last step, we conducted temperature-dependent measurements that illustrated a decrease in both spatial coherence length and temporal coherence time (τ_c) at elevated temperatures. The observed decreasing trend suggests thermal activation of momentum transfer processes. Moreover, the saturation of τ_c at around 370 fs exhibited at the low temperature regime is consistent with a coupling to acoustic phonons [2]. The results of this work provide insight into the phase diagram of interlayer excitons and help towards the investigation of a potential realization of a Berezinskii-Kosterlitz-Thouless (BKT) transition.

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INDISTINGUISHABLE PHOTONS FROM THE QUANTUM DOT BIEXCITON CASCADE

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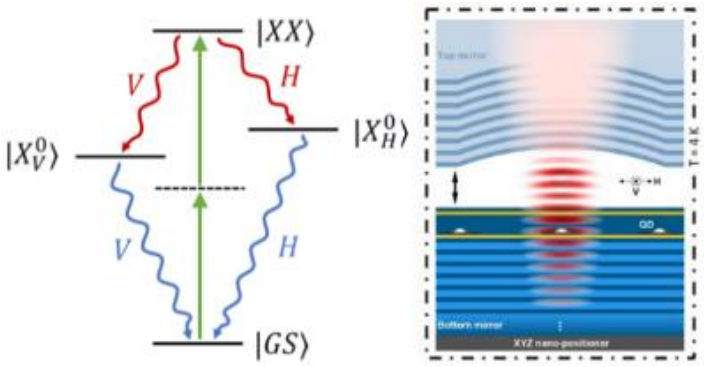
Certain quantum optical technologies rely on the development of sources of entangled photon pairs with properties such as high repetition rate and deterministic emission of a high purity entangled state. Additionally, the indistinguishability of subsequent emitted photons is essential for applications relying on photon interference such as entanglement swapping [1]. In self-assembled quantum dots, on-demand polarization entangled photon pair generation is possible via the biexciton cascade scheme shown in Figure 1. Upon closing the fine structure splitting between the H and P polarized exciton levels, deterministic generation of entangled pairs was shown [2]. Yet during the process, effects such as exciton lifetime jitter can greatly impact the indistinguishability between two consecutive photons from the biexciton (XX→X) or exciton (X→ GS). It was shown that engineering the lifetime imbalance between the two transitions has an impact on the said indistinguishability [3], with achieved values about 80% [4]. In this work, we used the high tunability of our Fabry-Perot open-microcavity single photon source [5] to selectively Purcell enhance the relative lifetime of the transitions. By tuning the cavity into resonance with the biexciton, the visibility of the biexciton-exciton transition was increased to 93% and that of the exciton to ground state transition to a similar value. In the complementary case (cavity mode in resonance with the exciton), the indistinguishability values are small. Thereby, we show that the full indistinguishability data set follows the theoretical predictions in [3], suggesting that the generation of high-quality polarization entangled photon pairs is achievable with a biexciton cascade.



(Left) In self-assembled quantum dots, two electron-hole pairs can bind to form a biexciton with two separate polarization decay channels that are used to pro-duce entangled photon pairs. (Right) An open microcavity is used to enhance and preferentially couple out photons resonant with the cavity mode.

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CAN QUANTUM LIGHT BEAT CLASSICAL UNCERTAINTY RELATIONS?

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Within the scope of attosecond science, ultrafast atomic and molecular phenomena are studied by means of ultrashort coherent lasers pulses and light-matter interactions. Historically, a vast majority of works in this field have used the semi-classical framework, treating the matter quantum mechanically while modeling the electromagnetic (EM) field classically, which suffices to describe most of the experimental physics [1].

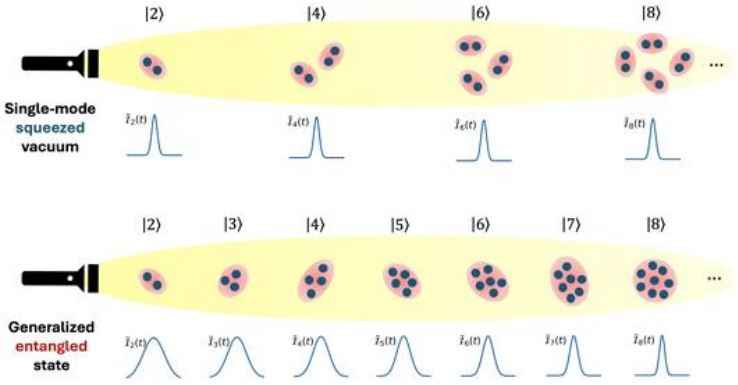

Figure 1. Non-classical states of light shown as superpositions of entangled photon-number states. Blue curves are the temporal profiles of the pulse at each photon-number state.

However, the last few years have seen a surge of activity questioning the assumption that this approximation captures all the relevant physics [2-4]. For instance, it is of interest to study ultrafast two-photon phenomena in which both photons are absorbed virtually at the same time. For a classical field, it is known that the only way to enforce short delay times is to make the pulse itself short, which limits the spectral information it can carry as it will be affected by Fourier broadening [5].

In this work, we show that this limit can be broken using non-classical states of light, such as the squeezed vacuum, with which the photons' arrival times can also be controlled by means of time-frequency entanglement. We derive general expressions for the relation between the bandwidth of a single light beam in free space and the variance of the delay between photon-pairs and show that there is a general trend of the non-classical effect being inversely proportional to the average number of photons. However, arbitrary resolution on the delay-bandwidth uncertainty relation can still be achieved at high intensity with a class of hyper-bunched light fields, for which the pulse duration varies at each photon-number state (Figure 1). Thus, we demonstrate that it is possible for a bright light field to maintain spectral resolution while ensuring arbitrarily faster two-photon absorption.

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OPTIMAL MODE PARAMETER ESTIMATION WITH GAUSSIAN QUANTUM STATES

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Quantum mode parameter estimation focuses on determining the parameters that define the shape of the electromagnetic modes occupied by a quantum state of radiation. Typical examples include estimating time delays and frequency shifts, which are crucial in applications like radar and lidar. Reference [1] introduced a comprehensive framework for mode parameter estimation, demonstrating that many quantum state designs can reach the Heisenberg limit— surpassing classical approaches. This naturally raises the question: among all quantum-enhanced , which one is truly optimal? To address optimality, it is essential to identify the relevant resources for a given mode parameter estimation task, enabling fair comparisons across quantum states. These resources are connected to the mode basis that diagonalizes the generator of the mode transformation. For instance, since the generator of a time shift is diagonal in the frequency domain, the relevant resources become the mean frequency and bandwidth of the quantum state. We derive a fundamental upper bound for Gaussian states on the achievable precision expressed in terms of these resources and identify optimal Gaussian quantum states that saturate this bound. Remarkably, these optimal states assume a particularly simple form when represented in the eigenbasis of the generator.

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CLOSE ENCOUNTERS BETWEEN PERIODIC LIGHT AND PERIODIC ARRAYS OF QUANTUM EMITTERS

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Strong light-matter coupling encountered in cavity quantum electrodynamics has enabled controlled manipulations of quantum states at the few-excitation level, building one of the main workhorses for future quantum technologies. Periodically structured surfaces (metasurfaces), such as metamaterials or photonic crystals, on the other hand, have evolved as a standard tool to manipulate classical electromagnetic fields. Here, we propose a framework for strong light-matter coupling in which collective excitations of quantum emitter arrays are strongly coupled to a metasurface. We provide a few-mode quantization of the electromagnetic field in this system. Our formalism is based on identifying the diagonal and cross momentum-resolved spectral densities within the unit cell. By fitting these spectral densities to a set of interacting and lossy modes, we obtain the relevant quantized electromagnetic modes that couple to the emitters. Importantly, this framework enables the study of nonlinearities arising from the quantum emitters, allowing for the analysis of the corresponding polariton-polariton interactions. Our approach paves the way to future ab initio investigations of quantum effects arising in metasurfaces that are strongly coupled to emitters.

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THEORY OF QUANTUM DOT PHOTON PROPERTIES: INFLUENCE OF HOT STATES AND PHONONS

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Semiconductor quantum dots are promising single photon sources. For applications in quantum communication, the generation of indistinguishable photons is essential. Indistinguishability is influenced by various decoherence mechanisms; in this work we focus on the temperature dependent interaction with the solid-state environment.

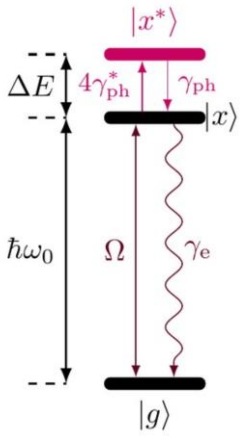

Figure 1. Scheme of the driven two-level system with hot states.

To study the temperature-dependence of photon indistinguishability we consider a semiconductor quantum dot as a two-level-system and treat the non-Markovian phonon environment using the process tensor formalism ACE [1]. We then extend the model to include hot states (or higher excited) states [2], that are coupled via temperature-dependent transitions, as shown in Figure 1.

Our study shows that including hot states plays a crucial role in the decrease of the indistinguishability as a function of temperature. While for temperatures below around 15K, the pure dephasing coupling is dominant, for temperatures above 15K the decrease is dominated by the hot state dynamics. We compare our theoretical results with experimental data and find an excellent agreement (Fig. 2).

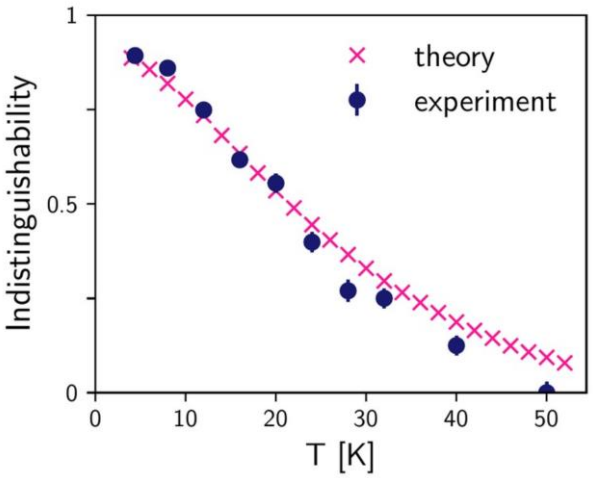

Figure 2. Temperature-dependence of the indistinguishability.

These insights help clarify the limitations of often assumed two-level system dynamics and can guide the development of quantum dots as applicable single photon sources.

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ENHANCED SPIN-COHERENCE IN A GaAs QUANTUM DOT

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Semiconductor quantum dots are promising candidates for photonic quantum technologies such as cluster state generation or distant spin-spin entanglement. In these systems spin decoherence is mainly caused by magnetic noise from the host nuclei. Droplet-etched GaAs quantum dots are particularly of interest due to their low strain environment compared to established InGaAs quantum dot systems. The homogeneous nuclear ensemble in GaAs quantum dots is affirmed by successful electron spin decoupling from the host nuclei with T2CPMG > 100 µs [1]. Through Ramsey interferometry the electron coherence time T2* is determined, which simultaneously gives rise to the nuclei's temperature. We implement an all-optical nuclear-spin cooling scheme [2,3,4] to increases electron spin-coherence time in a GaAs QD from 3.9 ns to 78 ns after Rabi cooling and up to T2* = 608 ns after feedback cooling [4] (see Figure 1). The electron coherence is maintained for much longer times than pulse sequences for photonic quantum logic gates as well as the radiative decay time which paves the way for a coherent spin-photon interface. The next steps include the optical control of a hole spin in a GaAs quantum dot to probe the underlying nuclear-spin interaction mechanisms, where the cooling procedure was already successfully implemented in a microcavity-assisted InGaAs QD [5].

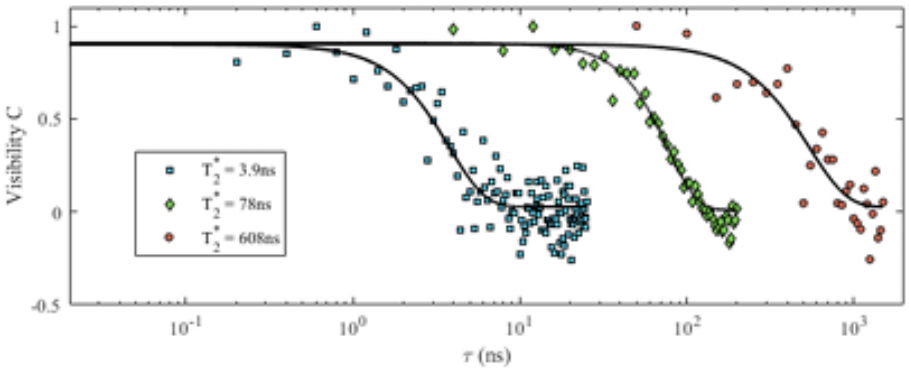

Figure 1: Ramsey visibility before cooling (blue), after Rabi cooling (green), and after feedback cooling (red). [4]

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A SOURCE OF HIGHLY NON-DEGENERATE ENTANGLED PHOTON PAIRS WITH SUB-100 KHZ BANDWIDTH

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For my Ph.D. thesis, I will present the design and implementation of an ultra-narrowband, cavity-enhanced entangled photon source tailored for hybrid quantum networks and quantum sensors. Leveraging spontaneous parametric down-conversion (SPDC) inside a bow-tie cavity, our source will generate highly non-degenerate, polarization-entangled photon pairs with sub-100 kHz linewidth. The signal photon will be locked to the Rubidium D2 line (780.24 nm) for quantum memory compatibility, while the idler photon will reside in the telecom C-band (~1550 nm) for low-loss fiber transmission and integration with optomechanical systems. This system will enable high-fidelity entanglement, robust cavity stabilization, and spectral engineering for direct interfacing with quantum memories and narrowband quantum sensors, laying foundational infrastructure for scalable quantum communication and precision sensing applications.

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MOLECULAR EMITTERS: NON-IDEAL TWO-LEVEL-SYSTEMS IN LIGHT & MATTER INTERACTIONS

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In the context of light-matter interactions between organic chromophores and confined photons of (plasmonic) nano resonators [1], we present a novel approach accounting for the complexity of both the light and the matter constituents of hybrid systems. # By describing the internal dynamics of the molecular emitters with ab-initio theory [2,3] and quantizing the inhomogeneous electromagnetic field in (plasmonic) nano resonators, with just a few modes [4,5], we achieve a quantum description of light-matter interactions that takes into account the inherent homogeneous and inhomogeneous broadening of material excitations as well as the radiative/non-radiative losses of optical nano-cavities.

We show that while dynamic disorder introduced by the molecular degrees of freedom lifts degeneracies otherwise preserved within a two-level-system approximation, strong light-matter interactions are preserved. Losses remain the limiting channel of light-matter interactions within plasmonic optical cavities. Yet, we identify a symmetry-broken scheme that allows to circumvent deactivation channels mediated by the so-called pseudo-mode. Overall, we propose a molecule-nanoparticle set-up that through coupling to a cylindrical cavity mode allows for intermolecular energy transfer between molecules tens of nm apart, largely overcoming the limits imposed by both Dexter and Forster energy transfer mechanisms.

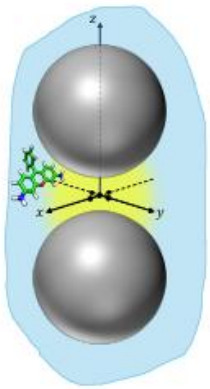

Figure 1. Rhodamine chromophores in the gap a silver nanoparticle dimer

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EFFICIENT QUANTUM CIRCUITS FOR SIMULATIONS OF DISSIPATIVE LIGHT-MATTER INTERACTIONS IN NANOCAVITY-EMITTER SYSTEMS

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Metallic nanocavities enable strongly localized light-matter interactions by confining electromagnetic fields at subwavelength scales, drastically enhancing the interaction with quantum emitters such as molecules, quantum dots or nitrogen-vacancy (NV) centers in diamond. This enhanced interaction has found applications in areas like molecular spectroscopy [1] or control of non-classical photon states. [2]

The dynamics of a single emitter coupled to a nanocavity can be obtained in an efficient manner through the Jaynes-Cummings Hamiltonian [3]. However, the brute force classical simulation of nanocavity-emitter systems becomes intractable when scaling up to many emitters in the presence of dissipative processes like the metallic losses or the emitter spontaneous emission. In this work we develop quantum circuits to simulate the dissipative dynamics of 1D weakly coupled nanocavity-emitter networks. These dynamics are encoded using ancilla-assisted techniques [4] which are then benchmarked using simulators and IBM quantum processing units (QPUs). We further improve the hardware efficiency of our circuits using mid-circuit measurements and classical control-flow constructs [5]. Our results show very favorable scalability of the circuit depth for exploring complex cooperative phenomena in many emitters networks using near-term devices.

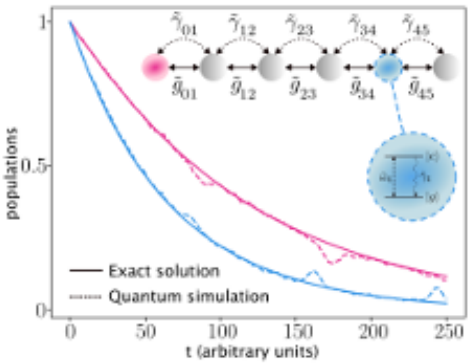

Figure 1. Quantum simulations of the population dynamics of the left-most (dashed hot pink curve) and second-to-last (dashed turquoise curve) emitter in a chain of six two-level emitters. After the removal of the nanocavity, the emitter dynamics can be obtained by adding appropriate cross-decay ($\tilde{\gamma}_{ii+1}$) and effective couplings ($\tilde{g}_{ii+1}$) terms. Simulation results are compared to the exact solution (solid curves).

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PURCELL-ENHANCED SINGLE-PHOTON QUANTUM DOT SOURCES IN N-IN GATED STRUCTURES OPERATING IN THE TELECOM C-BAND

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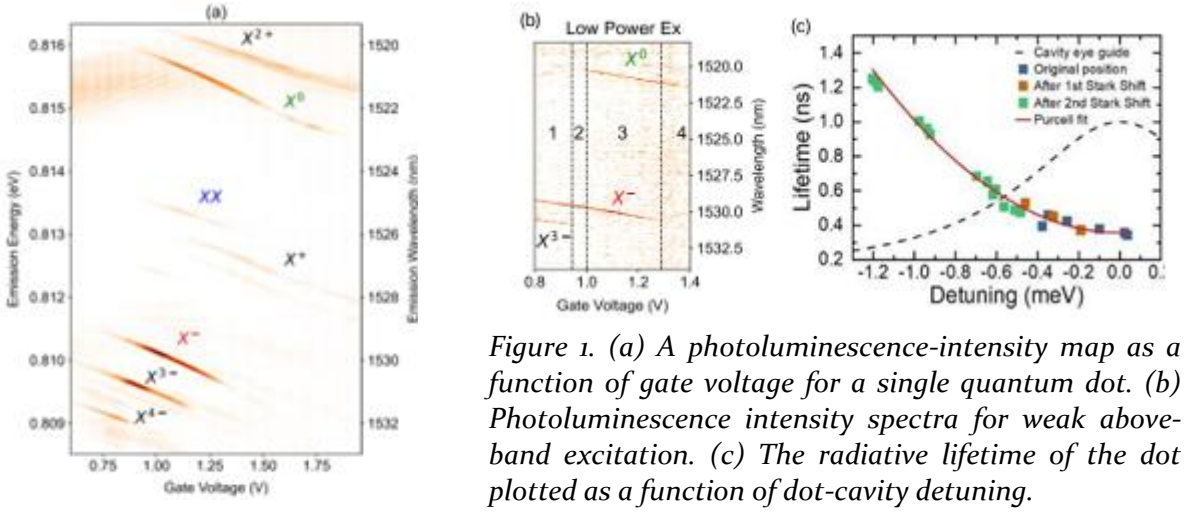

Figure 1. (a) A photoluminescence-intensity map as a function of gate voltage for a single quantum dot. (b) Photoluminescence intensity spectra for weak above-band excitation. (c) The radiative lifetime of the dot plotted as a function of dot-cavity detuning.

Single-photon sources are crucial in the development of quantum-secure telecommunication networks. Quantum dots, particularly those that emit in the telecom C-band, are promising candidates due to their deterministic emission, high brightness and tunable optical properties [1]. Integrating quantum dots into gated structures helps reduce charge noise and spectral diffusion. Similarly, coupling them to photonic devices enables Purcell enhancement – a phenomenon that increases the spontaneous emission rate – and improves in-plane photon collection efficiency. In this work, InAs/InP dots grown by droplet epitaxy in a metal-organic vapor-phase epitaxy (MOVPE) reactor are presented. We introduce a novel n-i-n gated structure and demonstrate, for the first time, electrical Stark tuning and charge control of quantum dots emitting in the telecom C-band [2]. Tuning ranges of up to 2.4 nm are achieved, marking a key milestone toward enabling advanced functionalities in quantum communication applications. We further demonstrate a reduction in emission lifetime by embedding the quantum dots in low-mode volume L3 photonic crystal cavities [3]. These exhibit a short radiative lifetime of 340 ps, corresponding to a Purcell factor of 5. This is achieved using a phonon-sideband pulsed excitation scheme and fine-temperature tuning to bring the dot closer to resonance with the cavity mode.

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EXCITON-POLARITONS BASED IN HALIDE PEROVSKITES AT ROOM TEMPERATURE

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Exciton-polaritons are solid-state quasi-particles presenting properties lying in between light and matter such as non-linear interactions (from the excitonic Coulomb repulsion), fast propagation (arising from the photonic component). The interest of polaritons[1] spans from the fundamentals of correlated light-matter interaction to emergent applications such as ultra-thin lasers, optical amplifiers, logic gates and even emulators of lattice-like Hamiltonians. We implement a monolithic microcavity composed of two mirrors, a bottom distributed Bragg reflector made of 10 alternating SiO_2 and TiO_2 layer pairs, and a top silver mirror of ~20 nm thickness. Between them, we deposit 2D layered phenethylammonium (PEA_2PbI_4) perovskites of ~100 nm thickness. As a cavity spacer, we use PMMA polymer, whose thickness is controllably tuned to bring the photonic and excitonic modes in energy resonance. The vertical design of the planar microcavity system is guided by transfer matrix method simulations. We measure the dispersion relation of polaritons under white light (left-hand side of Fig. 1 panels) and weak, non-resonant driving for three exciton-photon energy detunings (right-hand side of Fig. 1 panels) resulting from the different PMMA thicknesses. Interestingly, under circularly polarized, non-resonant (3.06 eV) CW laser driving, the lower polariton branch emission follows the circular pump polarization. Under the same excitation conditions, the exciton does not exhibit a circular degree of polarization, due to the slower decay of bare excitons, as opposed to exciton-polaritons. Finally, photostability experiments for long exposure excitation time scales (min) also reveal that the polariton emission is more resilient than bare excitons, indicating that strong coupling serves as a protection for excitons [2].

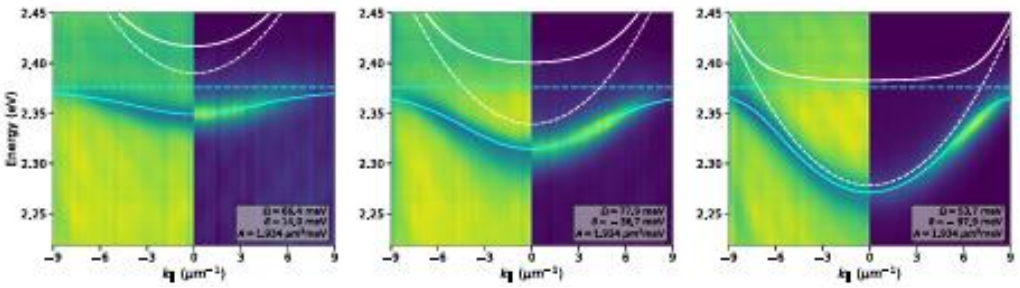

Figure 1 – Dispersion relation of the lower polariton branch at room temperature, under weak, non-resonant driving, for three different cavity detunings (the lower polariton branch redshifts as the PMMA layer gradually

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IMPROVING LINEAR OPTICAL STATE PREPARATION WITH INVARIANT SUBSPACES

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Not all photonic states can be connected with a passive linear interferometer, which makes preparing arbitrary states challenging with linear optics. Many state preparation algorithms simply parametrize the unitary of an interferometer and optimize it to produce the desired state, which is computationally expensive. In this work, we use invariant subspaces to reduce the cost of optimizing these state preparations. When a state preparation is allowed, the input and output density matrices can be decomposed into invariant subspaces, which gives a necessary condition for linear optical state preparation. This decomposition narrows the search space of possible unitaries, reducing the number of parameters from quadratic (in the best case) to no reduction (in the worst case). Once we have this parametrized unitary, we can apply the usual algorithms to optimize the preparation of the output state with a reduced computational cost. In addition to improving state preparation algorithms, this new parametrization may help to classify the equivalence classes of states connected via linear optics.

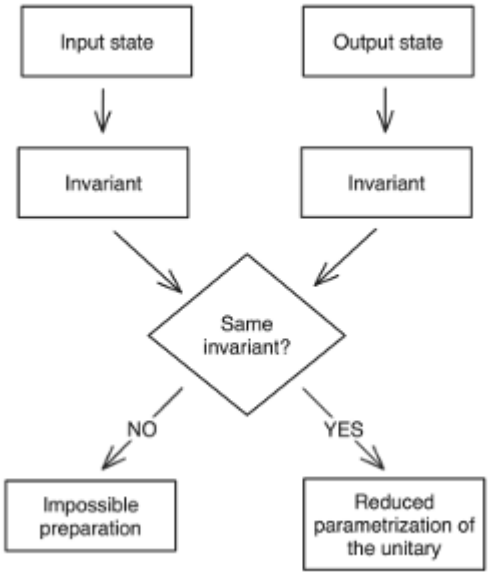

FIG. 1: State preparation flow diagram. First, we check if the input and output invariants are equal. If they are not, the preparation is impossible. If they are equal, we can parametrize a unitary that preserves the invariant subspaces, reducing the number of free parameters in the unitary.

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TEMPORAL COHERENCE OF SINGLE PHOTON EMISSION FROM HEXAGONAL BORON NITRIDE DEFECT AT ROOM TEMPERATURE

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Efficient single-photon sources are essential for quantum photonic applications, generating photonic qubits, the building blocks for quantum computing, metrology, and communications. Solid-state single-photon sources offer higher generation efficiency than heralding ones, such as spontaneous parametric down-conversion sources [1]. Moreover, solid-state sources offer a broad span of emitters with different properties, which can be tailored for specific photonic applications. In particular, defects in hexagonal boron nitride (hBN) emerge as promising room temperature single photon sources for communication, showing high brightness, and a relatively narrow linewidth emission [2]. In this work, we measure the pure dephasing time of the single photon emission of a defect in a hBN nanocrystal at room temperature. We drive this defect using non-resonant excitation and we characterize the standard properties of its emission such as the spectrum, lifetime, and antibunching. Then, we access the pure dephasing time of the single photon emission measuring its mean wave-packet overlap in a Michelson interferometer. The observed dephasing time of the zero-phonon line is a few hundred femtoseconds, four orders of magnitude faster than the spontaneous decay time. In the next experiments, the coupling of this emitter to a photonic mode in a cavity may accelerate its lifetime via the Purcell effect, increasing the brightness of the emission, and potentially increasing the coherence time of the wave-packet [3].

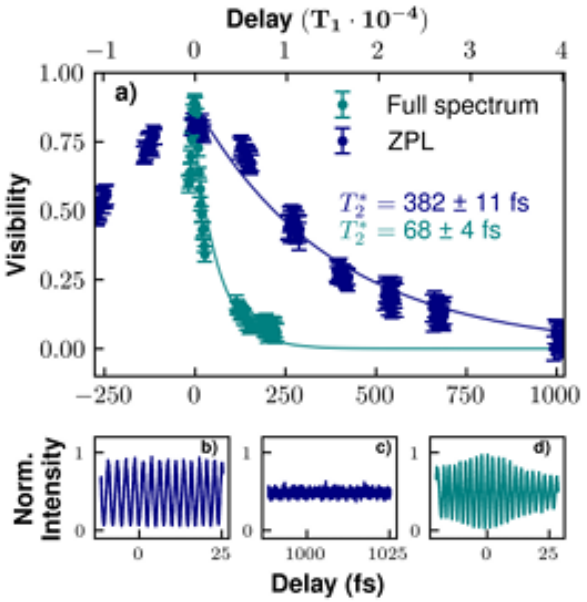

Figure 1. (a) Visibility decay as a function of delay in a Michelson interferometer for two different filterings of the hBN defect spectrum. (b-d) Interference fringes at different delays.

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