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Appendice II

A1 Integrated source of entangled photons by transition metal dichalcogenides

Transition metal dichalcogenides (TMDs), *e.g.*, MoS_2, $MoSe_2$, WS_2 and WSe_2, all semiconductors with wide optical transparency (750-4000 nm), have huge optical nonlinearity. This offers the unique opportunity to achieve high nonlinear efficiency over nanoscale thicknesses. Such layered materials are low-cost, easy to process and, due to their structure with strongly covalently bound monolayers held together by weak van-der-Waals interactions, allow an easy and bond-free integration with CMOS technology without lattice mismatch constraints. In addition, their linear and nonlinear optical properties can be strongly modified by electrical doping, which can be easily implemented using graphene contacts which ensure atomically perfect interfaces.

By virtue of the exceptional nonlinear properties of TMDs and the possibility of cavity integration and phase-matching in waveguide geometries, it is possible to integrate on-chip ultra-compact devices with extremely high nonlinear conversion efficiency opening new frontiers for engineering on-chip integrated nonlinear optical devices.

Spontaneous Parametric Down Conversion (SPDC), recently observed, pave the way for integrating layered semiconductors into photonic circuits as on-chip entangled photon sources for quantum information processing, exploiting their huge second-order optical nonlinearity, which can be increased even further by easy van-der-Waals integration with nanophotonic structures such as metasurfaces, waveguides and nano/microresonators.

Silicon is the targeted photonic platform for the source integration.

The project should:

1) provide a the design of TMD based on-chip SPDC source of entangled photons also involving nanophotonic structures such as metasurfaces, waveguides and nano/microresonators in Silicon photonic platform;

2) realize a proof-of-concept of, TMD based, on-chip source of entangled photons

A2 Single-photon detector integrated into a photonic circuit

Silicon based integrated optics has reached new levels of scale and performance in quantum optics. Many passive and active devices required for quantum optics applications (pump removal filters, Mach-Zehnder interferometers, multiplexers, multi-mode interference waveguide couplers, etc.) have been demonstrated by the silicon quantum photonics community.
A key requirement for quantum applications is the capability of detecting single photons. In the wavelength range below ≈ 800nm this is typically done by means of Si-based single photon avalanche diodes (SPADs). Such devices cannot be used in combination with Si waveguides due to the contradictory requirements of exploiting Si transparency for photon propagation/manipulation and Si absorption for photon detection.
Single photon detectors based on superconducting nanowires can be integrated on silicon, however their operation requires cryogenic temperatures (< 10K) thus weakening one of the main advantages of quantum optics over solid-state-based approaches to quantum technology.

For the delivery of practical, integrated, quantum photonic circuits, a single-photon detector, operating in the C- and O- band telecom windows, with an operation temperature as close as possible to room temperature, and never below liquid nitrogen temperature (77K), is required.
Another fundamental requirement for the integration of single photon detector into silicon based photonic circuits is the compatibility with CMOS foundry processes. Germanium based SPADs could be a possible solution, being Ge highly compatible with CMOS foundry processes and its absorption coefficient covers the 1310 nm and 1550 nm bands.

The availability of such single photon detector would be of utmost relevance also for photonic circuits based on platforms different from silicon, like $LiNbO_3$.

The project should:

1) provide a detailed design of the single-photon detector in the 1310 nm e 1550 nm windows operating at temperatures above 77K;

2) realize a prototype of single-photon detector for heterogeneous integration in a photonic circuit (to be used within photonic platforms different from Si, like $LiNbO_3$).

3) develop the fabrication process to integrate the single-photon detector in a Si waveguide;

4) realize a prototype of single-photon detector integrated in a Si photonic circuit.

3 Integration of single-photon sources into $LiNbO_3$

Scalable quantum photonic architectures are among the main players of the so-called second quantum revolution. A key enabling functionality of this framework is the generation and manipulation of on-demand quantum states of light in low-loss reconfigurable integrated photonic devices. Thanks to its broad transparency window that spans from 350 nm to 5000 nm and strong electro- and nonlinear-optical effects, $LiNbO_3$ is an ideal candidate for the realization of integrated quantum photonic circuits.

A fundamental open issue in the development of quantum optical communication, is the integration and the scalability of sources and detectors in the optical domain.

Deterministic single-photon sources based on atoms and molecules are among the most promising and scalable systems to attain ultimate integration. In NQSTI, Spoke 4, bright on-demand single-photon sources, based on organic molecules in solid-state systems and colloidal quantum dots are developed. Such single-photon sources need to be integrated in $LiNbO_3$ platforms to enhance and redirect the single photons into and from the free space. However, the realization of integrated hybrid photonic circuits where deterministic single-photon sources are integrated into $LiNbO_3$ platforms remains an open challenge that has no yet been tackled.

On the other hand, probabilistic sources of entangled photons constitute the most widespread platforms to deploy quantum communication protocols such as quantum cryptography, quantum repeaters, quantum teleportation, and photonic based quantum computation since they can be operated at room temperature. Here the development of nanoscale sources for the generation of entangled photons represents one of the major tasks in quantum optics.

The recent developments in $LiNbO_3$ nanofabrication, based e.g., on focused ion beam milling, along with the availability of commercial thin films on insulator opened doors to the possibility to tackle both: 1) the fabrication of optical nanocavities and metasurfaces, monolithically fabricated on $LiNbO_3$ circuits, to in- and out-couple light in free-space but also to shape the emitted light properties, such as polarization and wavefront; 2) the realization of compact $LiNbO_3$-based sources of entangled photons using SPDC where the $LiNbO_3$ thin film serves as an active host substrate for nanostructures that confine and enhance light and hence SPDC.

The project should:

1) provide a detailed design of nanoscale $LiNbO_3$-based sources of entangled photons using SPDC in the telecommunication window;

2) provide a detailed design of hybrid platforms based on deterministic single-photon sources and monolithic metasurfaces to in- and out-couple single photons in the near-infrared to and from integrated $LiNbO_3$ photonic circuits to free-space;

3) develop the fabrication process to integrate both photon sources in a $LiNbO_3$ waveguide;

4) realize a prototype of a room temperature entangled photon source in a $LiNbO_3$ photonic circuit;

5) realize a prototype of in- and out-coupler of single photons integrated $LiNbO_3$ photonic circuits and demonstrate its ability to couple single photons generated by a molecule or by a colloidal semiconductor quantum dot.

A4 Development of high-quality quantum limited parametric amplifiers based on engineered arrays of Josephson junctions as interfaces for quantum circuits

High-fidelity multiplexed readout of superconducting qubits in circuit QED cannot be achieved with state-of-the-art semiconductor amplifiers, such as HEMTs. The first amplification stage must have quantum-limited noise and high enough gain to suppress the noise added by a subsequent HEMT amplifier. Superconducting metamaterials based on engineered arrays of Josephson junctions can be exploited to make wide bandwidth traveling-wave parametric amplifiers (JTWPAs) in the microwave range. It has been shown that JTWPAs could have added noise as low as the standard quantum limit, although this has not yet been achieved.

The quantum circuits developed under Spoke 5 and 6 must be coupled with quantum-limited superconducting microwave parametric amplifiers in the C-band (4-8GHz), thus requiring the integration of different materials and technologies. This is to be achieved by employing technologies (e.g. niobium trilayer technology) that enable the realization of devices with a high level of uniformity and reliability. The project is expected to:

1) provide the design and simulation of the parametric amplifier for the C-band with at least 10 dB gain;
2) deliver a fully characterized prototype of a parametric amplifier for the C-band ready to be integrated in one of the qubit measurement set-ups provided by Spoke 6.

A5 Development and characterization of high-quality superconducting resonators for integration into quantum circuits operating in the low photon-occupancy regime

High-quality factor superconducting resonators in single and coupled configuration have many applications of interest to Spoke 6. Superconducting quantum circuits integrate qubits and arrays of qubits with high-quality factor (possibly larger than 10e6) resonators to achieve long relaxation times: this is crucial for realizing devices such as quantum memories, superconducting quantum networks or multi-qubit arrays for quantum sensing. In particular, in circuit QED superconducting resonators are used for qubit protection and readout as well as qubit–qubit coupling. The quality factor of superconducting resonators is affected by many mechanisms, but the two level system (TLS) losses in dielectrics are often dominant in the single photon regime. Superconductors used for the resonator contribute typically through the “metal-air” interface due to oxides and impurities.

The project shall investigate non-traditional materials, such as niobium nitride or tantalum, for the realization of superconducting microwave resonators that exhibit high quality factors for very low probe powers (i.e. in the few photon regime).

The project is expected to deliver a batch of prototypes of high-quality factor resonators designed by Spoke 6 to be integrated with qubits fabricated exploiting the facilities of NQSTI.

A6 Development of wide-bandwidth superconducting microwave amplifiers to be integrated in single-photon detectors for quantum sensing applications

Continuous detection of single photons in the microwave domain has many applications in association with superconducting quantum circuits, semiconductor quantum dots, spin ensembles, and mechanical quantum oscillators. Traveling-wave parametric amplifiers based on Josephson junction arrays (JTWPA) can be designed to replace conventional broadband HEMT amplifiers in various single photon detection schemes for quantum sensing. In the search for rare events (e.g. due to dark matter axions conversion in high magnetic fields), microwave photons in cavities can be detected by integrated J-TWPAs with bandwidths up to and above the X-band (8-12GHz) and robust against stray magnetic fields.

This range of frequencies requires innovative designs, state of art technologies and sophisticated testing instrumentation that are not commonly available. The project is expected to:

1) provide the design and full simulation of a first JTWPA targeting the X-band with at least 10 dB gain;
2) deliver one fully characterized prototype designed to work in the X-band and ready to be integrated in one of the measurement set-ups provided by Spoke 6.

A7 Firmware and middleware for reading and controlling frequency-multiplexed superconducting qubits

For the control and characterization of quantum circuits with frequency-multiplexed superconducting qubits, the framework provided by the open source middleware Qibo is exploited in NQSTI Spoke 6. Specifically, the open source Qibolab, Qibocal and Qibosoc libraries are used, which enable the control of RFSoC (Radio Frequency System on Chip) boards based on FPGAs (Field Programmable Gate Arrays) with which the microwave signals required to operate the superconducting qubits are generated and read.

The project funded under this call consists of the implementation in the Qibolab library of all the functionality required for the use of the integrated quantum hardware developed as part of NQSTI's Spoke 6: this includes the mechanism for conversion from quantum circuit gates to microwave pulses, generation of a pulse sequence through remote connection protocols, scheduling of tasks for pulse sequence evaluation, reconstruction of measurement results, and implementation and automation of qubit calibration algorithms.

Adaptation of the Qibosoq server to be installed on RFSoC boards to integrate the open source QICK firmware with the Qibo framework is also required.

A8 NIR-UV photon detector arrays with energy and number resolution

For quantum simulators and quantum metrology based on the photonics platform, photon (NIR-UV) detectors play a key role. In many applications of interest to NQSTI, it is critical to use efficient and fast detectors with the inherent ability to resolve the number of incident photons and their energy, in the absence of dark counts. The most promising technology with these characteristics is the one of Transition Edge Sensors (TESs), which determine the amount of energy deposited by interacting quanta via the temperature change measured by a superconducting sensor. For the goals of Spoke 6, the call is funding the development of a prototype TES array to be integrated with a multiplexed readout system and an appropriate single photon source, both of which are to be fabricated by the institutions participating in NQSTI's Spoke 6.

The developed detector array, given the goals of Spoke 6, must be designed to have the following characteristics:

1) at least 4 TESs;
2) energy resolution (E/ΔE) of at least 4;
3) detection efficiency greater than 90%;
4) response time less than 1 μs.

The project is expected to:

1) provide the complete design and simulation of the array TES detectors;
2) deliver a fiber-optically coupled array included in appropriate packaging. The packaging should be designed in consultation with the Spoke 6 partners to also accommodate the multiplexed readout chip.