Generation, routing, and non-linear manipulation of single photons via surface plasmons for quantum nanometrology and sensing

Objective of thesis (4 or 5 line overview):

- Controlled routing and focusing of externally generated single photons with surface plasmons in nanostructured metals
- Control over single photon emission in quantum dots via coupling to surface plasmons of nanostructured metals
- Generation of high nonlinearities exploiting electromagnetic hot spots generated by surface plasmons for photon routing and modulation
- Theoretical development of precision metrology and sensing devices based on these concepts

Description of thesis subject under the following sub-headings (maximum 5 pages)

Scientific Quality and Innovation

The main goal of this PhD project is the development of a methodology for the generation and manipulation of single photons on the nanoscale, utilizing concepts from nanophotonics that can circumvent the diffraction limit of light. Such a study is immensely timely, taking advantage of recent developments in the field of plasmonics on unprecedented control over light far below the wavelength. The programme of work will hence be instrumental in developing an understanding of both the possibilities and the constraints of combining quantum optics with nanotechnology, here in particular as regards to control over single photons. The PhD project is structured into two work packages, WP 1 on achieving control over externally and on-chip generated single photons via nanohole arrays, and WP 2 on the optimization of nanoplasmonic structures for single photon control. The achieved results will further lead to an assessment of the feasibility of nanoscale precision nanometrology and sensing devices based on these quantum plasmonic concepts. The outcome of this work will involve first demonstrations of controlled generation and manipulation of single photons in a nanoscale environment, which is a prerequisite for highly miniaturized quantum-based sensing devices. We now briefly describe the two work packages.

WP 1: Conditioned single-photon generation and modulation via light-controlled surface plasmon excitation in nanohole arrays

We propose to use the surface-plasmon-based photon-blockade mechanism in order to gate the emission of single-photon wavepackets via the relaxation of SPs (surface plasmons) excited by a low-intensity pumping field. A first task will be the preliminary study of the statistical properties of the light emitted by SP-relaxation in the absence of blockading mechanisms. This could shine interesting new light on the supposed linearity of the light-SP-light interconversion process. Gold or silver metallic nanostructures will be fabricated using electron beam lithography or focused ion beam milling, focusing particularly on nanohole arrays. Circular, closely spaced holes as well as elliptical holes will be studied to achieve optimal field enhancement effects and thus strong effective third-order nonlinearities needed to control the SP excitation. The structure will be covered with a nonlinear polymer, which will be on the interface as well as in the holes of the structure. An existing single-photon source based on parametric down conversion will be used as a first step. The photons from this beam will be sent through the metallo-dielectric nanostructure with sub-wavelength holes. They can tunnel through it via excitation of surface plasmon polaritons and/or localised surface plasmons, essentially in the same way as many-photon light beams do. In this way, single photons observed behind the nanostructure shall exhibit the same...
properties as incoming (signal) photons. The following step would be an analogous investigation when the blockading strategy is active, with the task of looking for photon anti-bunching (witnessed by the statistical sub-Poissonianity) of the re-emitted light in a photon-blockade scenario. In order to control the single photon transmission, an additional laser beam of a different frequency to the signal will be introduced. Switching the control light on/off will induce changes in the refractive index of the polymer with the Kerr-type nonlinearity, and, thus, will change the resonant conditions of the SP excitation on the signal light frequency. Thus, the presence of the control light illumination will block the transmission of single photons through the nanostructure. The first goal of the project is to observe stable nonclassical photon statistics of the field emitted by SP. The quantum state of the field can also be reconstructed using the homodyne scheme. The efficiency of the “on demand” character of the single photon generation depends on the ability of switching on/off the blockade mechanism, which requires a theoretical design and the experimental implementation of strategies for faster switching times than those currently allowed by the state of the art technology. The nanostructure parameters for SP excitation, nonlinearity enhancement and properties of the transmitted single photons will be studied. Transient processes that should be determined by the relaxation time of the nonlinear polymer and lifetime of SP excitation will also be studied. This will determine the speed of on/off switching.

In a second step, we will change from controlling externally generated single photons to direct control and manipulation to photons generated on chip. For this, the nanohole layer will be covered with an additional layer of quantum dots, and changes in the fluorescence properties mediated by the nanohole array studies, with and without the modulation beam present. While initially not at single photon level, these studies should yield valuable information on the development of a single – photon source based on a single quantum dot in proximity to a plasmonic nanohole. Depending on the outcome of the initial studies in this part of the project, a single quantum dot source with plasmonic modulation control will be developed.

WP2: Optimization of the nanoplasmonic structure for control over single photons

While WP 1 focused on the, from the plasmonic point of view, well-understood nanohole geometry, in this work package we will assess the potential of further miniaturization of the plasmonic component via an investigation of quantum dots coupled to metallic nanoantennas. Focusing initially on the bow-tie geometry, we will assess the routing of photons generated in quantum dots coupled to nanoantenna arrays, utilizing as a main tool direct reciprocal space imaging of the directivity of emission of photon emission mediated via the interaction with the plasmonic nanoantenna array. Studies of nonlinear control over the emission via embedding into a nonlinear polymer layer as described to above will follow, and the feasibility to extending these concepts to the single photon level assessed. The ultimate goal here is the controlled routing and modulation of single photons from a single quantum dot coupled to a nonlinear single metallic nanoantenna.

All the necessary nanofabrication facilities for generation of nanoantennas down to gap sizes on the order of 10 nm are available on campus, which puts us in a unique position to address single photon manipulation in nanometric volumes.

The knowledge gained from these two mainly experimental work packages will directly feed into wider theoretical work within our group, for the development of novel quantum devices for single-photon generation, quantum metrology, and high-sensitivity sensing. In collaboration with the existing doctoral training centre in quantum technologies at Imperial, we will ensure swift translation of our findings to industry, making use of our wide network of collaborators and partners, such as BAE Systems, Toshiba, as well as leading international centres of excellence such as NTT. This will also include a joint initiative with the Imperial College Business School. Furthermore the Physics Department at Imperial has a dedicated industry club, and the student will be provided with the opportunity to present his research to an audience drawing from a wide variety of industries at a yearly industry open day event. All impact activities will further be coordinated with existing programmes in our centre for doctoral training.