Quantum measurement with entangled-photon states

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Abstract

Two photons in a pair generated in the nonlinear process of spontaneous parametric down conversion (SPDC) are, in general, strongly entangled. Accordingly, they contain extremely strong energy, time, polarization, and momentum quantum correlations. This entanglement involving more than one pair of quantum variable has served as a powerful tool in fundamental studies of quantum theory. It is now playing a significant role in the development of novel information processing techniques and new optical measurement technologies.

Introduction

Entangled-photon states produced by the non-linear optical process of spontaneous parametric down-conversion are composed of photons that are created with strongly correlated properties that remain so even after the photons have propagated to widely separated locations in space. These strong quantum correlations, naturally present between down-conversion photons, allow for uniquely quantum mechanical and often superior forms of measurement to be performed. These quantum states are also capable of encoding information, providing robust coherence properties associated with entanglement that allow this information to be transported and transformed in unique ways. Their resistance to the decoherence phenomena that have hampered other approaches to quantum information processing has put entangled-photon optics in a position of importance in the area of quantum communication. Quantum information research has served as an excellent vehicle for developing fundamental principles of quantum mechanics creating a scientific basis for the rapid development of quantum technologies in the 21st century. The rapid development of quantum cryptography originally initiated in academic research labs has been recently pursued by several industrial centers. The overall success in quantum science and engineering has stimulated development of multiple tools operating exclusively according to the rules of quantum mechanics. They have clear advantages over existing techniques in many areas of research and technological measurement.

Traditionally, in optical metrology absolute measurement always requires *a priori* knowledge of basic parameters of light before its interaction with a physical system. Although most physics measurements are carried out with independent particles, it is the collective nature of entangled particles that reveals the most fascinating and unexpected aspects of the quantum world. One curious aspect of the behavior of a pair of particles in an entangled state is that, though each individual particle exhibits an inherent uncertainty in behavior, the joint entity of an entangled pair can exhibit no such uncertainty. As an example, while the time of arrival of an individual particle may be totally random, an entangled pair must always arrive simultaneously. This unique aspect of entanglement leads to a self-referencing capability in timing. Similar non-classical entanglement of two photons could be demonstrated in their polarizations (spin), energies (frequency) and direction of propagation (wave vector). Such a property offers a unique tool for carrying out absolute measurements without relying on an *a priori* calibrated optical standard by making use of entangled photons. We outline the implications and significance of entanglement exploitation for the development of a new type of optical measurement - quantum optical metrology.

Entangled photons first became of great interest in probing the foundations of quantum mechanics. Debates surrounding the foundations of quantum mechanics have been ongoing since the introduction of the theory, particularly since the 1930's, with entangled-photon states often playing a central role in providing essential empirical information. Entangled states of increasingly better quality have continually been sought in order to better and better differentiate quantum behavior from classical phenomena. Entangled quantum systems are composed of at least two component subsystems and are described by states that cannot be written as a product of independent subsystem states. The nonlinear optical process known as spontaneous parametric down-conversion (SPDC) has become the most widely accepted method for creating entangled quantum states in optics. New, high-intensity sources of SPDC have been developed over the last two decades. Spontaneous parametric down-conversion of a laser photon into a pair of photons is said to be of one of two types based on the satisfaction of phase-matching conditions, as either type I or of type II, corresponding to whether the two photons of the down-conversion pair are produced with the same polarization or orthogonal polarizations, respectively. The two photons of a pair, often called signal (s) and idler (i) for historical reasons, can also leave the down-converting medium either in the same direction or in different directions, known as the collinear and non-collinear cases, respectively. (See **Figure 1**)

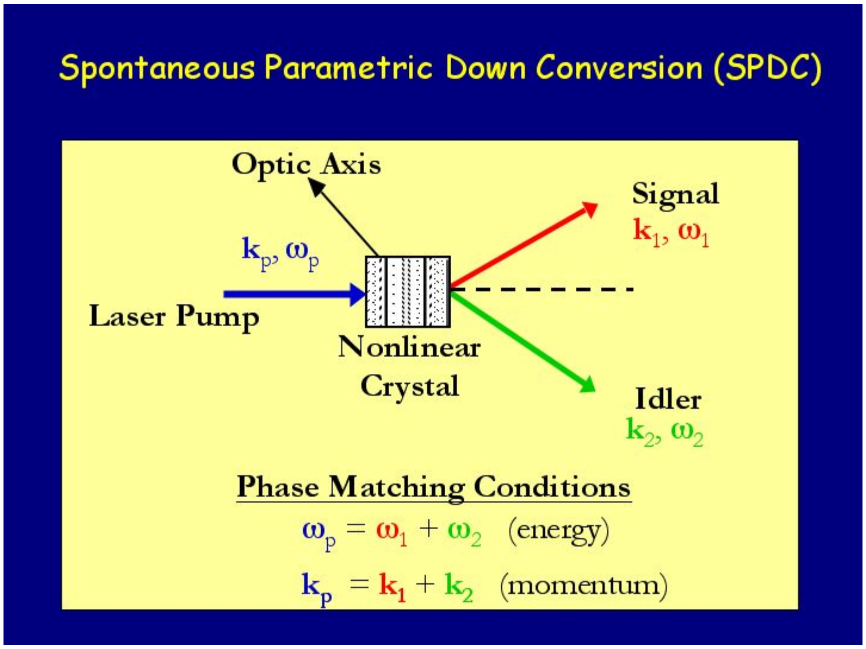

Figure 1

Spontaneous parametric down conversion (SPDC)

The medium where down-conversion takes place is usually some sort of birefringent crystal, for example, potassium dihydrogen phosphate (KDP), possessing an optical nonlinearity. Upon entrance to a nonlinear crystal, there is a small probability (on the order of 10^{-7}) that a given photon from the incident pump beam will be down-converted into a photon pair (see **Figure 1**). If down-conversion occurs, these conserved quantities are carried into the resulting photon pair under the constraints of their respective conservation laws, with the result that the phases of the corresponding wave-functions match, which are referred to as the phase-matching conditions. Down-conversion photons are thus produced in two spectral cones, one for each photon, within which two-photons appear each as a pair of photons on opposite sides of the pump-beam direction (See **Figure 1**). Entanglement between two particles involving one particular quantum variable, such as spin, was discussed by David Bohm in his famous 1954 Quantum Mechanics book [1]. In the mid-1980s, Hong, Ou and Mandel [2] created noncollinear, type-I phase-matched SPDC photon pairs in KDP crystal using an ultraviolet continuous-wave (cw) laser pump in a seminal experiment empirically demonstrating the strong temporal correlation of the two down-conversion photons. The main step in the development of practical quantum correlation and quantum entanglement tools was the development of ultra-bright sources of correlated photons and development of novel principles of entangled states engineering. This also includes entangled states of higher dimensionality and entangled quantum states demonstrating simultaneous entanglement in several pairs of quantum variables (hyper-entanglement). The successful development of such features has opened a way for quantum optical designers to the construction of optical measurement approaches that achieve higher accuracy and grater amount of information about the system under investigation in comparison with their classical counterparts.

Quantum photometry

Historically, the idea of calibrating single-photon detectors without any need for using traditional blackbody radiation sources was the first example of practical utilization of non-classical correlations between two photons produced in the nonlinear process of spontaneous parametric down conversion. (See **Figure 2**) This technique has paved the way for several other quantum measurement approaches that exploit non-classical correlation and later benefited from the full power of quantum entanglement utilization. The unique possibility of non-local self-referencing present in the optical system that is distributed in space-time is the main advantage of quantum correlation and entanglement [4].

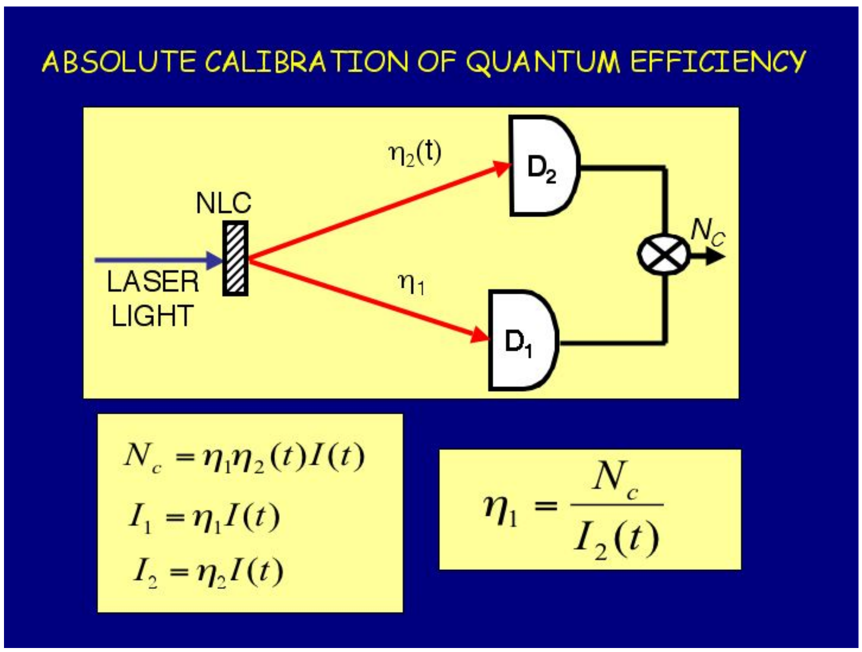

Figure 2

Using non-classical timing correlation between two photons for calibrating quantum efficiency of photodetectors

Another uniquely quantum feature lies in the spontaneous nature of the SPDC process. The probability of spontaneous photon pair creation is governed by the principles of quantum mechanics and can serve as a universal and independent reference for calibrating the optical radiation intensity and brightness (radiance) [3, 4]. The accuracy of such universal quantum referencing is limited only by the accuracy to which we know the values of major universal quantum constants. The additional significant convenience that is provided by the parametric nonlinear process consists in the possibility of accurately measuring the infrared signal brightness by detecting visible idler radiation without the need of using infrared detectors, which are usually very noisy and have low sensitivity [4]. These two approaches established foundations of new area in optical metrology – quantum photometry.

Quantum Ellipsometry

A question that arises frequently in the metrology of surfaces is the following: How does one measure reliably the reflection or transmission coefficient of an unknown sample? The outcome of such a measurement depends on the reliability of both the source and the detector used to carry out the measurements. If they both are absolutely calibrated, such measurements would be trivial. Since such ideal conditions are never met in practice, and since high precision measurements are often required, a myriad of experimental techniques have been developed over last century to circumvent the imperfections of the devices involved in these measurements. One optical measurement setting in which high-precision measurements is a necessity is ellipsometry, in which the polarization of light modification by the surface is used to study parameters of substrates, a technique established more than a hundred years ago. Ellipsometers have proven to be an important metrological tool in many arenas, ranging from the semiconductor industry to biomedical applications. They are particularly useful when the reflective properties of the material depend on its topological, geometrical, and chemical properties. Folded and unfolded protein detection in the drug discovery process and polarization scatterometry for critical dimensions evaluation in semiconductor lithography are just two examples where ellipsometry can be extremely useful these days.

Classical and quantum ellipsometry

To carry out *ideal* ellipsometry, one needs a perfectly calibrated source and detector. Various approaches, such as null (See **Figure 3** - left) and interferometric techniques, have been commonly used in ellipsometers to approach this ideal. A novel technique has recently been proposed for obtaining reliable ellipsometric measurements based on the use of twin photons produced by the process of spontaneous optical parametric downconversion (SPDC). (See **Figure 3** – right) The technique makes direct use of polarization-entangled photon pairs emitted through SPDC. This approach effectively comprises an interferometric ellipsometer, although none of the optical elements usually associated with constructing an interferometer are utilized, thanks to the power of nonlocal quantum correlations. Instead, polarization entanglement itself is harnessed to perform interferometry and to achieve ideal ellipsometry.

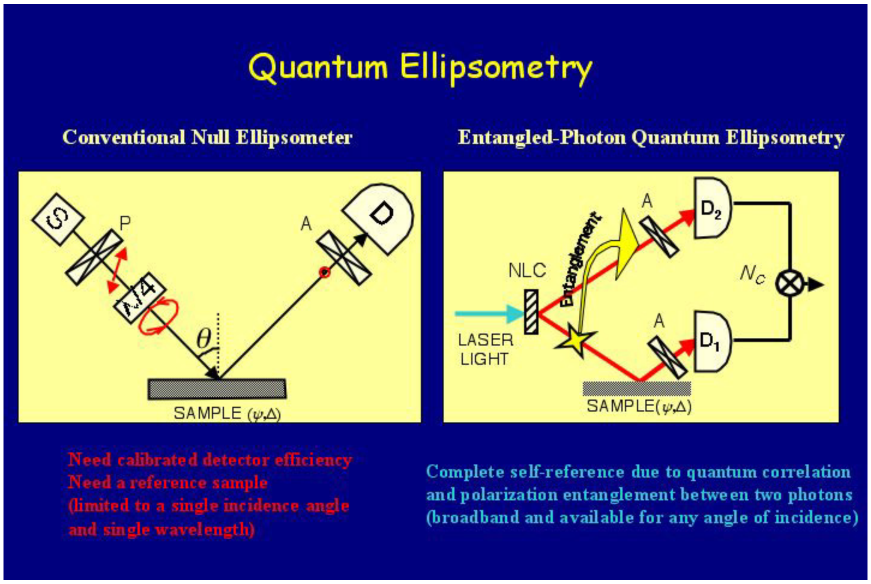

Figure 3

The theoretical foundations of single-frequency quantum ellipsometry for biophysics and nanophotonics applications have recently been developed. The first experimental implementations of correlated-photon and entangled-photon ellipsometry have indicated the potential of quantum polarization measurement [5]. Both the amplitude and phase modulation of polarized light due to surface structures are captured by the real and imaginary parts of measured polarization density matrix. Any classical approach would require performing two independent experiments to recover a similar quantity of information.

Quantum optical coherence tomography (QOCT)

Optical coherence tomography (OCT) has become a versatile and useful biological imaging technique, particularly in ophthalmology, cardiology, and dermatology. It is an interferometric scheme that makes use of a light source of short coherence time (broad spectrum) to carry out axial sectioning of a biological specimen. (See **Figure 4** – left). The axial resolution is enhanced by increasing the spectral bandwidth of the source (submicrometer resolution has recently been achieved by using a light source with a bandwidth of 325 nm). However, as the bandwidth is increased, the effects of group-velocity dispersion become increasingly deleterious for testing inner layers of tissue. Various techniques have been used in attempts to counteract the effects of dispersion, but these usually require *a priori* knowledge of the dispersion intrinsic to the specimen.

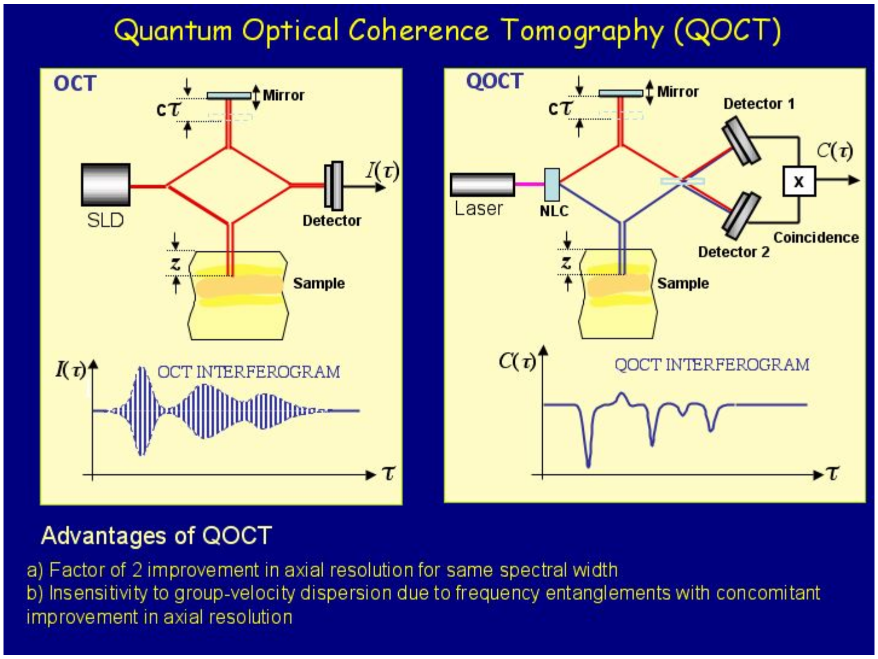

Figure 4

Conventional OCT and quantum optical coherence tomography (QOCT)

A quantum version of OCT makes use of an entangled twin-photon light source. (See **Figure 4** – right). One particular merit of quantum-optical coherence tomography (QOCT) is that it is inherently immune to dispersion by virtue of the frequency entanglement associated with the twin-photon pairs. The non-classical effect of dispersion cancellation is at the heart of QOCT approach, promising higher spatial resolution and more precise tissue modification diagnostics at the sub-micron level. Moreover, for sources of the same spectral bandwidth, the entangled nature of the twin photons provides a factor of 2 enhancement in axial resolution relative to conventional OCT. A correlated though non-entangled twin-photon light source (which is also nonclassical) is characterized by a factorizable state. Such a source would provide an intermediate enhancement in resolution of a factor of square root of 2 when the spectrum is Gaussian. However, the benefit of dispersion-cancellation does not accrue in this case. The basic physical principles of quantum version of optical coherence tomography for sub-micron biomedical imaging have recently been developed and demonstrated in a model environment [6].

Engineered entangled-photon sources

The development of integrated periodically-poled nonlinear structures has recently opened the road to the practical implementation of flexible and compact sources of entangled states. The intelligent engineering of the SPDC spectrum has enabled researchers to produce novel entangled states that have not been available from nature directly. Sources of high intensity entangled-photon flux have already revolutionized the area of quantum cryptography, bringing it into the real world outside research labs. Because of interferometric nature of optical coherence tomography OCT, it achieves high axial resolution mainly by using the short temporal coherence length of the light source, thus allowing it to be enhanced by the use of broadband sources such as superluminescent light-emitting diodes and ultrashort pulsed lasers. For QOCT, this means that in order to become compatible and even superior in resolution for biomedical coherence imaging applications totally new entangled-photon sources with ultra high spectral bandwidth must be developed.

It has been shown that quasi-phase matching (QPM) can be used to substantially enhance the spectral width of the entangled two-photon state produced in the down conversion process, while simultaneously maintaining its specific frequency anticorrelation [7]. QPM provides a feasible alternative to conventional phase matching and QPM engineering opens up new possibilities for intelligent design of specialty entangled-photon states. The longitudinal variation of QPM period (chirping) strongly affects the spatiotemporal properties of entangled photon pairs. The merit of a longitudinally chirped QPM is that it permits many different signal and idler photon wavelengths to be phase matched at different positions inside the nonlinear crystal, broadening the spectral content of the two-photon state. Chirped QPM down conversion offers a very broadband source for dispersion-canceled QOCT, providing the sub-micron level of lateral resolution that is not degraded with penetration depth inside the tissue.

Future challenges and perspectives

The telecommunication industry is coming back from the recent downturn and has revised its plans for deployment of 40 Gb and even faster networks in the near future. This has put rather heavy pressure on optical engineers to develop high-resolution techniques for evaluating chromatic and polarization mode dispersion (PMD) with an adequate resolution. It has been shown that without identifying and carefulyl accounting for such detrimental features and without their active compensation, all future optical communication standards cannot actually function, due to dispersive spread of telecommunication signals. The use of quantum correlations has enabled the design of new, a more accurate technique for characterizing chromatic dispersion in fibers [8]. The addition of intrinsically quantum interplay between polarization and frequency entanglement in SPDC (hyper-entanglement) has given rise to a polarization mode dispersion measurement technique that utilizes the power of quantum polarization interferometry and provides an order of magnitude enhancement in the resolution of PMD measurement in comparison with the best existing devices available today [8].

The need for ultra-high resolution optical measurement is one of the novel challenges in biotechnology and semiconductor research and in industry. In several modern areas of science and technology, a clear crisis in ***non-invasive*** measurement technologies has appeared, as modern biophotonics and nanotechnology move towards creation and manipulation of ever-smaller features. For example, the dimensions of modern test proteins on a surface in drug discovery and of solid-state patterns in semiconductor manufacturing are well below the wavelength of light. The existing characterization techniques such as fluorescent-marker visualization in biophotonics and electron scanning microscopy in nanotechnology are intrinsically invasive techniques often modifying the physical and chemical structure of the materials and altering the performance of the device after its characterization.

Optical technologies can provide non-invasive evaluation while simultaneously satisfying the constraint of smaller than the wavelength dimensions when the broad range of spectral components is employed. For example, conventional spectroscopic ellipsometry has already found its way in testing the morphology of protein samples in drug discovery and critical dimensions evaluation in nanotechnology. The use of simultaneous frequency and polarization entanglement present in SPDC leads to a unique possibility of simultaneous measurement of phase and group velocity parameters in the same experiment. With ultra-broadband spectrum of entangled sources, one can expect that the contrast and resolution of quantum spectroscopic measurement of biological objects such a folded and unfolded proteins on a surface will be superior over their classical counterparts.

The next five to seven years will see the rapid development of quantum measurement technologies. The design and characterization of novel few-qubits entangled states specifically engineered to match the requirements of quantum measurement in biophysics and modern solid-state nanotechnologies will serve as fuel for this process. One of the signs of this new century is a greater role of industrial research and development centers in pursuit of quantum technologies. The early participation of industry is facilitating future acceptance of new quantum technologies by both scientific and industrial environments and their incorporation into wide practice by developing integrated quantum measurement devices (sensors) and compact quantum circuits. The effectiveness and the future impact of quantum ideas in the world of optical measurement will strongly depend on the ease with which researchers in industry will be able to adopt rather disruptive quantum changes and incorporate novel ideas into their research and development plans.

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