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Editorial

Quantum Optics: Theory, Methods, and Applications

Jesús Liñares * and Xesús Prieto-Blanco

Quantum Materials and Photonics Research Group, Optics Area, Department of Applied Physics, iMATUS/Faculty of Physics/Faculty of Optics and Optometry, University of Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain; xesus.prieto.blanco@usc.es

* Correspondence: suso.linares.beiras@usc.es

1. Introduction

It can be stated without a doubt that Quantum Optics is currently one of the liveliest fields in both fundamental physics and applied physics. In fact, quantum light states, i.e., photons, manipulated by photonic systems, have been used successfully to test many of the counter-intuitive predictions of quantum mechanics (such as quantum superposition, entanglement, teleportation, interaction-free measurement, non-cloning of unknown quantum states, and so on) and have provided very useful resources for the quantum optical information science. In fact, scientific community has recently recognised this achievement by awarding the Nobel Prize in Physics 2022 to A. Aspect, J. Clauser, and A. Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

At present, a great deal theoretical and technological efforts are being made to develop different applications based on quantum photonics, that is, exploiting the most technological part of Quantum Optics and applying the results to the wide field of quantum information science and technology. We can highlight different research fields, and the first of them is the study of quantum light states (representations and characterization of quantum states, quantum coherence, entanglement, and so on) [1–3]. This field is, in turn, closely related to different problems of semiclassical and fully-quantum light-matter interaction and accordingly to the development of quantum light sources (single-photon emission [4], spontaneous parametric down-conversion [5], ...) that are a fundamental tool in Quantum Optics. Another important research field corresponds to the development and testing of optical systems and methods for quantum optical communications (teleportation [6], quantum memories [7], and so on) and for quantum cryptography based on QKD with Discrete Variables (DVs) and Continuous Variables (CVs) [8–10], where different QKD protocols have been proposed, for example, the ones based on a single-photon (BB84 [11], ...), two-photons (DV-MDI [12], ...), two entangled photons (BBM92 [13], ...), and those based on the detection of the quantum optical field (homodyne detection), for example, the Discrete Modulation [14], Gaussian Modulation with squeezed states [15], CV-MDI [16], and so on. On the other hand, we have another important research on different methods also based on DV and CV for the design and experimental implementation of optical quantum-information processing (linear quantum optical computation [17], Gaussian quantum information [18], quantum random number generation [19], quantum walk [20], and so on) and for analog optical quantum simulation [21,22]. Likewise, different techniques and devices are being developed for quantum optical metrology and sensors based on quantum optical coherence and interference (metrology without absolute standards [23], the Heisenberg limit [24], sub-diffractive lithography [25], and so on). Finally,

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there is quite a significant amount of research devoted to the study of quantum imaging and its applications, for example, ghost imaging [26] and quantum optical coherence tomography [27].

In short, all these studies show that Quantum Optics is and will continue offering important results in the fundamental domain of quantum physics, for example, on the problem of the quantum measure [28] (related, in turn, to quantum decoherence, quantum non-locality, quantum-classical boundary, ...), or even on the quantum aspects of living systems (quantum biology [29], quantum neurobiology [30], ...), and obviously will continue developing and proposing new applications for a very long time, for example, those related to the quantum artificial intelligence [31], but likely Quantum Optics could also be a powerful tool to overcome the current limits of the own quantum paradigm.

2. An Overview of Published Articles

This Special Issue is only a small sample of this exciting and broad field of Quantum Optics in its theoretical and fundamental aspects about quantum light, its mathematical and experimental methods, and its applications. In particular, the contributions made in this issue can be classified in three mean areas: theory and methods for the representation and characterization of quantum light states (three contributions), theory and methods to obtain quantum light states sources (two contributions), and finally three applications with quantum light states (quantum cryptography, quantum optical coherence tomography, and quantum linear momentum transfer).

2.1. Representation and Characterization of Quantum Light States

In this first area we have a contribution devoted to present phase space methods, particularly the derivation of the Wigner function of quantum light states. It provides tools to both represent (Wigner representation) and capture nonclassical features of quantum states. The study is made for two-mode quantum states and extended to indefinite number of photonic excitations (Fock layers) [32], all of it with potential applications in quantum information science and technology.

A second contribution is related to the study on the limitations of the method based on the inseparability criterion [33] to identify and quantify two-mode Gaussian quantum entanglement of squeezed light states. It is shown, in particular, that when decoherence does not affect symmetrically both modes, then a missed detection of entanglement is produced, which is confirmed by the socalled positive partial transpose criterion. The results can have important implications in quantum information.

Finally, a third contribution provides a study on quantum noise, and in particular on quantum chaos [34], when two-mode coherent mixtures of single photons with coherent states, excited with different mean photon numbers, are used. The results show the effect of the quantum wave and corpuscular nature of light on the noise of quantum chaos and, moreover, provide a characterization of quantum light states closely related to the Fano factor.

2.2. Quantum Light States Sources

In the second area mentioned above we have a first contribution on corner reflector plasmonic nanoantennas for enhanced single-photon emission [35]. This work provides a hybrid solution to solve the contradiction between the two requirements to obtain efficient single-photon emission; that is, a small resonator volume is necessary to maximize interaction efficiency, while a large antenna mode volume is essential to achieve high emission directivity. The results of this work demonstrate that a well-designed corner reflector can significantly enhance photon emission directivity while also substantially

boosting the emission rate. It must be stressed that controlled single photon sources is a fundamental tool to achieve different quantum light states (superposition states, product states, entangled states, and so on) and implement quantum applications.

A second work develops a theoretical formalism for the generation of optical vortices fields with a given topological charge by using phased arrays of atoms. The study determines the least number of individual atoms necessary for the generation of such vortices, and, therefore, the possibility to obtain quantum light states with a given orbital angular momentum [36].

2.3. Applications with Quantum Light States

In this broad area three contributions have been collected. The first one corresponds to a new QKD protocol based on the Bell-state-exchange-parity (BSEP) protocol which is an interesting improvement over the BBM92 protocol, that is, it ensures an intrinsic and, therefore, efficient autocompensation QKD [37] encoded in polarization or spatial modes ("plug and play" QKD). Consequently, the distances and secret key rates are increased while retaining the advantageous MDI-QKD characteristics. Different devices, in both bulk and integrated optics, are proposed for spatial and polarization autocompensation, for measuring Bell states excited in spatial and polarization modes and so on.

A second contribution corresponds to the study of light-to-plasma momentum transfer which determines the optimum conditions to achieve a maximum linear momentum transfer; such a study is relevant in laser plasma betatron sources (X-ray sources) [38] and in many potential applications related to fusion ingnition, quantum plasmonics, and so on.

Finally, a third contribution presents an experimental technique based on polarization-sensitive quantum optical coherence tomography (PS-QOCT) to image and characterize birefringence effects in biological samples [39]. The ubiquitous type II SPDC quantum source (polarization entangled biphotons) is used to produce quantum interference (HOM interference) modulated by polarization in a Mach–Zehnder interferometer, and thus, birrefringence images of biological tissue samples are obtained.

3. Conclusions

In this Special Issue, contributions to different areas of Quantum Optics have been made. First of all, new theoretical aspects related to the representation and the characterization (capture of the nonclassicality) of quantum light states have been evaluated. A first theoretical aspect presented is the derivation and analysis of the two-mode Wigner function for one and several Fock layers; a second aspect is the analysis of the limits of the inseparability criterion to analyse two-mode Gaussian entanglement; and finally, a study of the noise of quantum chaos and its close relationship to the Fano factor has been presented. On the other hand, improved methods have been also proposed to produce quantum light states sources, a fundamental tool in Quantum Optics, in particular, an experimental system for getting enhanced efficient single-photon sources, and an experimental method to produce quantum states with a given orbital angular momentum. Finally, three applications have been proposed, one of them in quantum communications by using a Bell-states-exhange-parity protocol which allows the implementation of an intrinsic "plug and play" QKD system; another application is related to the light-to-plasma momentum transfer of interest in X-ray sources and fusion ignition; and finally an experimental study on polarization sensitive quantum optical coherence tomography to obtain birrefringence images of biological tissue samples. These results improve the theory, methods, and applications of Quantum Optics and provide interesting suggestions for future researching on quantum phase space, Gaussian entanglement, quantum single-photon sources, "plug and play" QKD systems, and quantum imaging.

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