Trends in Quantum Optics*

A Personal Perspective

Subhashish Banerjee and Arun M Jayannavar

Here, we review some of the recent developments in quantum optics. After a brief introduction to the historical development of the subject, we discuss some of the modern aspects of quantum optics including atom field interactions, quantum state engineering, metamaterials and plasmonics, optomechanical systems, PT (parity-time) symmetry in quantum optics, as well as, quasi-probability distributions and quantum state tomography. Further, the recent developments in topological photonics is briefly discussed. The potent role of the subject in the development of our understanding of quantum physics and modern technologies is highlighted.

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Keywords
Quantum optics, metamaterials, plasmonics, optomechanical systems, parity-time symmetry.

1. Introduction

Light is intimately connected to the existence of all forms of life. The systematic study of light is known as 'optics' and could be traced historically to [1]. The notion of light as an electromagnetic field was made clear by Maxwell, resulting in his celebrated work on what is now known as Maxwell equations. He showed that electromagnetic fields in vacuum propagate at the speed of light. The next step in the history of this subject were the questions raised by the Michelson–Morley experiment and the Rayleigh–Jeans catastrophe associated with black-body radiation. The former lead to the development of the special theory of relativity and the later to Planck's resolution, which provided the first seeds for the field of quantum mechanics. The notion of photon, essentially considering it as a particle, was first realized in Einstein's work on the photoelectric effect.

A large number of phenomena, related to optics, could be ex-

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plained by invoking the concept of photons involving a classical electromagnetic field along with vacuum fluctuations. It was soon realized, in the wake of experimental developments that to understand the full potential of the photon, one needs to treat it quantum mechanically. This lead to the development of the quantum theory of radiation, which in turn, was the precursor to quantum optics [2]. The photon provides an example of a simple quantum state labelled by, say, its horizontal and vertical polarizations as:

$$|\psi\rangle = c_1 |H\rangle + c_2 |V\rangle .$$

Here, $|\psi\rangle$, pronounced as *ket psi*, denotes the state of the system and is a vector and is an example of a *superposition* state. Also, c_1 and c_2 are in general, complex numbers such that the sum of squares of their modulus $|c_1^2| + |c_2|^2 = 1$. The states $|H\rangle$ and $|V\rangle$ can exist simultaneously with probabilities $|c_1|^2$ and $|c_2|^2$, respectively. This is the *surprising* content of quantum mechanics that makes it stand apart from classical physics. This feature can be used as a resource for achieving things not possible in the classical realms. Further, it should be noted that in quantum mechanics, we deal with operators characterizing the observables. For example, energy is represented by the operator $\hat{H}$ called the Hamiltonian of the system. Experiments typically involve making measurements of the operator on the state vector and what is obtained as a result of the measurement is the eigenvalue of the operator. A simple example of measurement would be a projection operator that acts on the state of the system to be measured and take it to the final state. A basic tenet of quantum mechanics is that the results of the process of measurement are probabilistic in nature, and is known as the Born rule.

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Quantum measurements are described, in general, by a collection $\{M_m\}$ of measurement operators, acting on the state space of the system being measured. The index m refers to the measurement outcomes that may occur in the experiment. If the state of the quantum system is $|\psi_i\rangle$ immediately before the measurement, then the probability that result m occurs is $\langle\psi_i|M_m^\dagger M_m|\psi_i\rangle$.

Here, $\langle\psi_i|M_m^\dagger$ is the Hermitian conjugate of the vector $M_m|\psi_i\rangle$. The measurement leaves the system in the state:

$$|\psi_i\rangle \to |\psi_f\rangle = \frac{M_m\,|\psi_i\rangle}{\sqrt{\langle\psi_i|M_m^\dagger M_m|\psi_i\rangle}}. \quad (1)$$

The measurement operators satisfy the completeness condition $\sum_m M_m^\dagger M_m = \mathbb{1}$, expressing the fact that probabilities sum up to one. For those operators M_m where $M_m^\dagger = M_m$ and $M_m^2 = M_m$, this reduces to the projection operators mentioned above.

Quantum optics provide tools to study the foundations of quantum mechanics with precision and is the cause of several developments in quantum information and quantum technology. An important development in quantum optics came with the formulation of coherent states [3, 4], which basically ask the question of what are the states of the field that most nearly describes a classical electromagnetic field. This was originally introduced by Schrödinger [5]. Classically, electromagnetic field has a well-defined amplitude and phase, a picture that changes in the quantum mechanical scenario. A field in a coherent state is a minimum-uncertainty state with equal uncertainties in the two variables, in this context, often termed as the two quadrature components. For example, this could relate to the standard deviation of two sets of operators, such as position and momentum. This was followed by the development of squeezed states, where fluctuations in one quadrature component are reduced below that of the corresponding coherent state.

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In the quest for characterizing the nonclassical behavior of photons, anti-bunching and sub-Poissonian statistics were investigated. The coherent field is represented by Poissonian photon statistics, in which the photons tend to distribute themselves uniformly, i.e., the variance of the photon distribution is equal to its mean. In contrast to this, in sub-Poissonian statistics, the variance is less than the mean and was, first experimentally demonstrated in [6]. The deviation from Poissonian statistics is quantified by the Mandel Q_M parameter, discussed below in the context of quantum correlations. A closely related albeit distinct phenomenon is that of photon antibunching. Photon bunching is the tendency of photons to distribute themselves in bunches, such that when light falls on a photodetector, more photon pairs are detected close together in time than further apart. In contrast to this, in antibunching, the probability of photon pairs detection further apart is greater than that for pairs close together. Both the phenomena of sub-Poissonian statistics and photon antibunching are purely quantum in nature.

A major technological development due to quantum optics has been the development of LASER (Light Amplification by Stimulated Emission of Radiation), where coherent states play an essential role. Quantum entanglement, which is the quintessence of the quantum world, has been experimentally demonstrated with photons and has proved to be a potential resource in quantum computation and communication. Spontaneous Parametric Down Conversion (SPDC) is a frequently used process in quantum optics, which is very useful for generating squeezed states, single and entangled photons.

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Having sketched the roots of quantum optics, we will, in the remaining part of this article, try to provide a flavor for some of the modern developments in the field. In this context, the following topics will be discussed: (a) atom-field interactions, (b) quantum state engineering, (c) metamaterials and plasmonics, (d) optomechanical systems, (e) PT (Parity-Time) symmetry in quantum optics, (f) quasi-probability distributions and quantum state tomography, and (g) topological photonics.

2. Atom-Field Interactions

A canonical model of quantum optics is the Rabi model, which deals with the response of an atom to an applied field in resonance with the atom's natural frequency. Rabi considered the problem of a spin-half magnetic dipole undergoing precessions in a magnetic field. He obtained the probability of a spin-half atom flipping from $|0\rangle = (1\ 0)^T$ or $|1\rangle = (0\ 1)^T$ to the states $|1\rangle$ or $|0\rangle$, respectively, by an applied radio-frequency magnetic field. Here, T stands for the transpose of the row matrix. In the context of quantum optics, Rabi oscillations would imply oscillations of the atom, considered as a two-level system, between the upper and lower levels under the influence of the electromagnetic field. The Rabi model led to the development of the well-known Jaynes–Cumming model, which is a generalization of the semi-classical Rabi model in the sense that it invokes the interaction of the atom and the single mode of the electromagnetic field in a cavity. In contrast to the semi-classical Rabi model, here, the electromagnetic field is quantized.

The Jaynes–Cummings model has provided a platform for numerous investigations, including those related to quantum computation. However, one needs to keep in mind that the quantum mechanical coherences are subject to decay due to interactions with the surroundings [7]. This leads to losses such as decoherence (i.e., loss of coherence) and dissipation, which implies a loss of energy. Hence, one must have a good understanding of these processes. Experimental progress in this direction is discussed next.

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2.1 *Experimental Studies on Decoherence Models*

In a series of beautiful ion trap experiments, the Wineland group [8] induced decoherence[1], and decay by coupling the atom to engineered reservoirs in which the coupling to, and the state of the environment were controlled. Here, the basic tool used was the coherent control of atoms' internal states to deterministically prepare superposition states and extend this control to the external (motional) states of atoms. The Haroche group [9] used cavity quantum electrodynamics (QED), i.e., the controlled interaction of an atom with an electromagnetic field in an appropriate cavity to bring out various aspects of decoherence. Microwave photons trapped in a superconducting cavity constitute an ideal system to realize some of the thought experiments that form the foundations of quantum physics. The interaction of these trapped photons with Rydberg atoms, effectively two-level atoms, crossing

[1] The loss of coherence due to interaction with the surroundings.

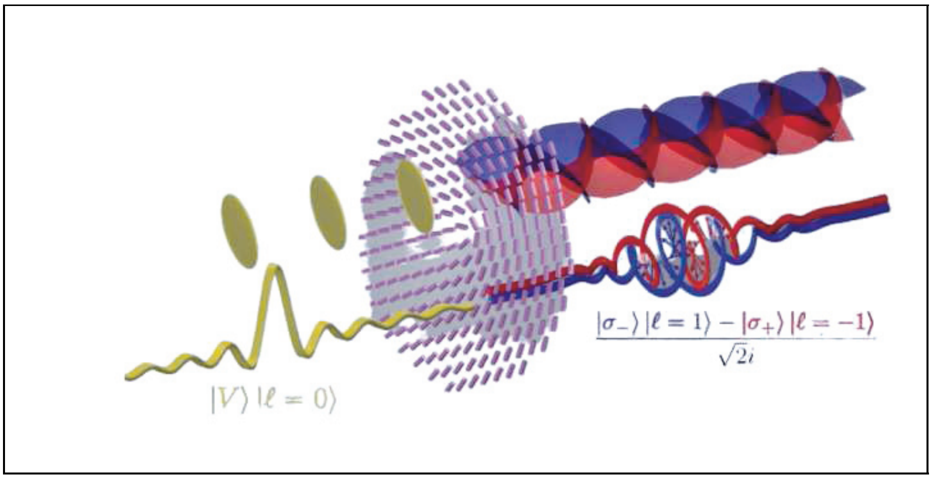

Figure 1. A single photon prepared in vertical linear polarization arrives from the left, as illustrated by the yellow electric field amplitude. This photon carries zero orbital angular momentum, as illustrated by the yellow flat phase fronts. The single photon passes through the metasurface comprising dielectric nano-antennae (purple) and exits as a quantum entangled state, depicted as a superposition of the red and blue electric field amplitudes and with the corresponding vortex phase fronts opposite to one another [11].

the cavity illustrates fundamental aspects of measurement theory.

2.2 *Quantum Correlations*

Here, we discuss the generation of various facets of quantum correlations, including entanglement arising from atom-field interactions. The widely studied among quantum correlations is the non separability of the quantum state of a system comprising two or more subsystems. In the simplest scenario, consider two systems with state vectors $|\psi\rangle$ and $|\phi\rangle$. A simple choice of the combined system would $|\psi\rangle \otimes |\phi\rangle$, a product state, where $\otimes$ denotes the tensor product. However, one can think of states of the form $(|\psi\rangle \otimes |\phi\rangle \pm |\phi\rangle \otimes |\psi\rangle)/\sqrt{2}$. By no means can one write this state as a product of two arbitrary states. Such states are called 'entangled states', a well-known example of which would be the Bell states [10]. A simple illustration generating a photon entangled state is shown in *Figure* 1. For two optical modes, represented by the operators $\hat{a}$ and $\hat{b}$, sufficient condition for entanglement is given by the Hillery–Zubairy criteria: (i) $\langle \hat{a}^\dagger \hat{a} \hat{b}^\dagger \hat{b} \rangle < |\langle \hat{a} \hat{b}^\dagger \rangle|^2$ (ii) $\langle \hat{a}^\dagger \hat{a} \rangle \langle \hat{b}^\dagger \hat{b} \rangle < |\langle \hat{a} \hat{b} \rangle|^2$. Here the angular brackets denote the operation of mean or average of the operators inside it with respect to the state under consideration. Another important nonclassical correlation exhibited by light is the sub-Poissonian statistics

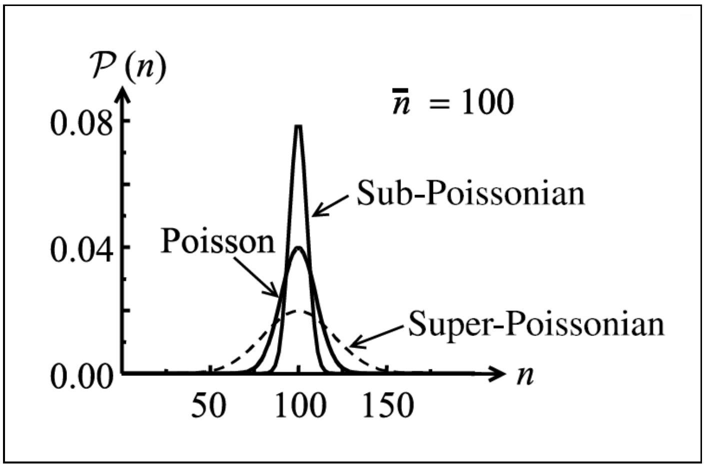

Figure 2. Probability distribution.

(see *Figure* 2). The coherent state of light is the closest classical description in which the probability of finding n photons has Poissonian distribution: $\mathcal{P}_n = \frac{\bar{n}^n}{n!} e^{-\bar{n}}$. Here, $\bar{n}$ is the average photon number and is equal to the variance, which in this case is $\Delta n^2 = \langle n^2 \rangle - \langle n \rangle^2 = \bar{n}$. Fluctuations are expected to increase the departure from the mean value, and consequently, one would have what is called the super-Poissonian light for which $\Delta n^2 > \bar{n}$, an example is the thermal light. However, it is found that light under certain circumstance shows sub-Poissonian behavior, i.e., $\Delta n^2 < \bar{n}$. This phenomenon has no classical analog and is a quantum effect. Mandel parameter defined by $Q_M = (\Delta n^2 - \bar{n})/\bar{n}$ measures the departure from the Poissonian statistics. Therefore, we have $Q_M < 0$, $Q_M = 0$ and $Q_M > 0$ for sub-Poissonian, Poissonian and super-Poissonian light, respectively.

3. Quantum State Engineering

Quantum state engineering (QSE) comprises three processes: (1) preparation, (2) detection, and (3) reconstruction of quantum states. In the recent past, QSE has appeared as the epithet for various proposals and experiments, preparing interesting states of the quantized electromagnetic field and atomic systems. Their motivation is the potential application of nonclassical states to tasks

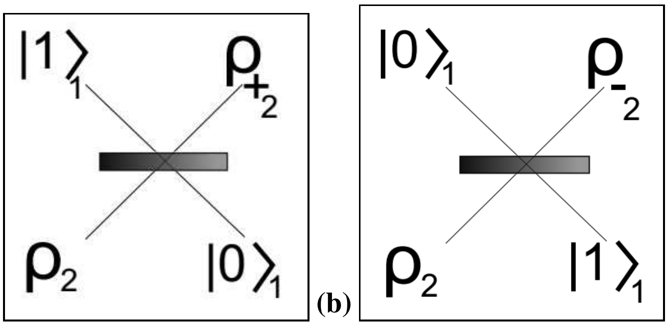

Figure 3. Beam splitter model for **(a)** photon addition in which a photon is added to the state ρ_2 and **(b)** photon subtraction ends up taking one photon from the state ρ_2, as a result of beam splitter interaction.

such as teleportation, quantum computation and communication, quantum cryptography, and quantum lithography, among others. These harnesses the power of quantum correlations, which occupy a central position in the quest for understanding and harvesting the utility of quantum mechanics. A field state having holes in its photon number distribution (PND) corresponds to a nonclassical state. A challenge in QSE is to make such holes by controlling their position and depths in the PND. A class of states in quantum optics of relevance to the present context are the intermediate states such as the binomial states (BS), formed by an interpolation of the number state, characterized by the number of photons in the state with the coherent state, as discussed above. The concept of hole burning has been extended to the atomic domain as well. Here, the generation of spin squeezing proceeds via hole burning of selected Dicke states (counterparts of the photonic number states), out of an atomic coherent state (counterparts of the usual coherent states), prepared for a collection of N two−level atoms or ions. The atoms or ions of the atomic coherent state are not entangled. But the removal of one or more Dicke states generates entanglement, and spin squeezing occurs for some ranges of the relevant parameters. Spin squeezing in a collection of two-level atoms or ions is of importance for precision spectroscopy.

Quantum state engineering can be studied using linear optics; in the form of photon added or subtracted using beam splitters.

QSE can be studied using linear optics; in the form of photon added or subtracted using beam splitters (BSs), as illustrated in *Figure* 3. An isomorphism can be set up between BS operations and angular momentum relations. Squeezed states are examples of nonclassical multiphoton states of light and can be generated from coherent states. Of special emphasis is the engineering of nonclassical states of photons and atoms, such as Fock states, macroscopic superposition states, and multiphoton generalized coherent and squeezed states that are relevant for applications in the forefront aspects of modern quantum mechanics. In recent times, advances have been made by combining linear and nonlinear optical devices allowing the realization of multiphoton entangled states of the electromagnetic field, either in discrete or in continuous variables that are relevant for applications to efficient quantum information processing. Multiphoton quantum states are carriers of information, and the manipulation of these by the methods of quantum optics has brought about a strong interface between the fields of quantum information and quantum optics.

4. Metamaterials and Plasmonics

Metamaterials are structured composite materials with periodic subwavelength sized unit cells. The subwavelength nature of the unit cells does not permit the wave to resolve individual unit cells, and permits the description of the composite material as an effective medium described by properties such as permittivity and permeability. Metamaterials are artificially fabricated materials, usually comprising nanoscale structures designed to respond to light in different ways. They have been extensively studied in the last two decades and have been used to demonstrate a wealth of fascinating phenomena ranging from negative refractive index to super-resolution imaging. In recent times, metamaterials have emerged as a new platform in quantum optics and have been used to carry out several important experiments using single photons. Sophisticated macro-scale structures have been used to create photon entanglement [12]. Recent advancements in on-chip quantum photonic circuits have lead to the development of integrated entangled photon sources. The metasurfaces made of high refractive index dielectric are resistive to plasmonic decoherence and loss. Silicon-based metasurfaces with nearly 100% efficiency make them candidates for quantum optics and quantum informa-

Metamaterials are structured composite materials with periodic subwavelength sized unit cells. They usually comprise nanoscale structures designed to respond to light in different ways.

tion applications. A simple illustration of a dielectric metasurface generating entanglement between the spin and the orbital angular momentum of photons is shown in *Figure* 1.

Plasmonics is a rapidly developing field at the boundary of physical optics and condensed matter physics. It studies phenomena induced by and associated with surface plasmons—elementary polar excitations bound to surfaces and interfaces of good nanostructured metals.

Electronic systems governed by the rules of quantum mechanics are hard to understand principally due to the strong Coulomb interactions between electrons. This makes many interesting systems difficult to comprehend via simple models as the many-body interactions and effects cannot be ignored nor properly described simplistically. The Maxwell equations that govern electromagnetism and the Schrödinger equation of quantum mechanics reduce to the same Helmholtz equations under certain circumstances. This can be employed to great effect to use light as a test-bed for quantum effects as the photon-photon interactions can be very small and can be accurately controlled via non-linear interactions of a medium. Electromagnetics has greatly benefitted in the past two decades from developments in metamaterials and plasmonics. Metamaterials having resonant unit cells have highly dispersive effective medium parameters whereby novel properties and phenomena not usually found in nature become accessible. The most famous examples are negative refractive index, perfect lenses with sub-diffraction image resolution, perfect absorbers of light, and media with extremely large anisotropy resulting in even hyperbolic dispersion for light. Similarly, plasmonics that concerns with the study and manipulation of surface electromagnetic waves on the surfaces of metals (electronic plasmas) and metamaterials, gives rise to enormous possibilities on structured surfaces. With great control that becomes possible on the dispersion of the two-dimensional surface plasmons as well as their coupling to radiative modes, plasmonics offers immense promise for the miniaturization of optical devices that are projected to supplant electronic devices due to the enormous bandwidths at optical fre-

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quencies.

It is known that surface plasmon waves preserve the entanglement of twin photons, which is understood by the coherent nature of the surface plasmon waves despite the coupling to dissipative modes in the plasmonic medium. Plasmonic systems are becoming crucial for quantum information purposes. Particularly as the interaction volumes become smaller and subwavelength, the interaction of the surface plasmons with emitting molecules or quantum dots becomes increasingly governed by quantum mechanics. The dissipative environment is, however, an issue, but the systems offer a neat platform to explore the role of decoherence for quantum systems as well.

The unique properties offered by metamaterials and plasmonic structured surfaces can offer new testing grounds for quantum theories. For example, surface plasmons on the interfaces of metals and nonlinear materials can offer deep insights into Anderson localization of interacting particles in two dimensions. Similarly, nonlinear metamaterials and nonlinear surface plasmonic structures can enable controlled experiments of quantum tunnelling in time retarded systems by studying evanescent electromagnetic waves. Note that an evanescent wave is an oscillating electric and (or) magnetic field that does not propagate as an electromagnetic wave but whose energy is spatially concentrated in the vicinity of the source (oscillating charges and currents). The easily modified photonic density modes here offer unique possibilities. The extreme control on the generation of and detection of light (microwaves in particular) make these a good platform for the implementation of many thought experiments that have hitherto been inaccessible in electronic systems.

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In recent times, different types of metamaterials have been studied. Thus, for example, one can have nanowires that use quantum dots as unit cells or artificial atoms arranged as periodic nanostructures. This material has a negative index of refraction and effective magnetism and is simple to build. The radiated wavelength of interest is much larger than the constituent diameter. Photonic bandgap materials, also known as photonic crystals, are materials that have a bandgap due to a periodicity in the material's dielectric properties. A photonic bandgap can be demonstrated with this structure, along with tunability and control as a quantum system. The bandgap in photonic crystals represents the forbidden energy range where photons cannot be transmitted through the material. Quantum metamaterial can also be realized using superconducting devices both with and without Josephson junctions and are being actively investigated. Recently, a superconducting quantum metamaterial prototype based on flux qubits was realized [13].

5. Optomechanical Systems

Recent experiments in cavity quantum electrodynamics (cQED) have explored the interaction of light with atoms as well as semiconductor nanostructures inside a cavity. Cavity quantum electrodynamics is the study of the interaction between light confined in a cavity and atoms, where the ambient conditions are such that the quantum nature of light becomes predominant. This field could be traced to the Purcell effect [14], which is connected to the process of spontaneous emission—a purely quantum effect by which the system transitions from an excited energy state to a lower energy state, emitting, in the process, a quantized amount of energy in the form of a photon. The Purcell effect is the process of enhancement of the system's spontaneous emission rate by its ambient environment. It is dependent on the quality Q factor of the cavity, which is a measure of the ratio of the energy stored to the energy dissipated. A good quality cavity would have a high Q factor.

Cavity quantum electrodynamics is the study of the interaction between light confined in a cavity and atoms, where the ambient conditions are such that the quantum nature of light becomes predominant.

Light carries momentum, which gives rise to radiation-pressure forces. Recent works have been able to study coupled cavity photonic systems to solid-state mechanical systems containing a large number of atoms [15]. In these systems, there is an optical cavity with a movable mirror at one end or a micro-mechanical membrane with mechanical effects caused by light through radiation pressure. Hence, cavity quantum optomechanics has emerged

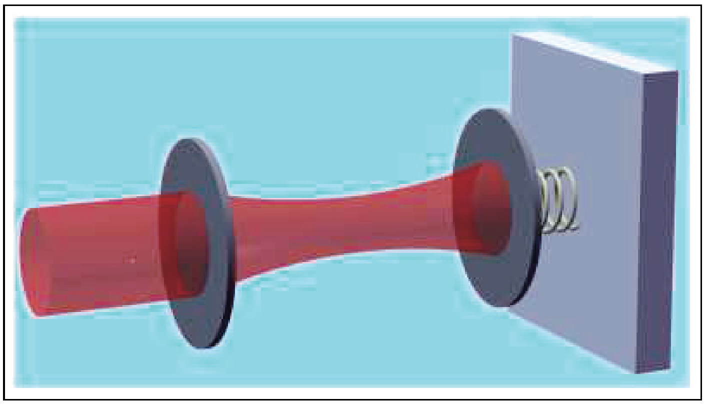

Figure 4. A typical cavity optomechanical system is driven by a laser. The left mirror is fixed while the right mirror is attached to the spring providing the mechanical mode in the system.

as a very interesting area for revealing quantum features at the mesoscale, where it is possible to control the quantum state of mechanical oscillators by their coupling to the light field. Recent advances in this area include the realization of quantum-coherent coupling of a mechanical oscillator with an optical cavity, where the coupling rate exceeds both the cavity and mechanical motion decoherence rate and laser cooling of a nanomechanical oscillator to its ground state. Furthermore, new experimental works open up enormous possibilities in the design of hybrid quantum systems whose elementary building blocks are physically implemented by systems of different nature.

Cavity optomechanical systems can provide a natural platform to induce an interaction between mechanical resonators because there is an intrinsic coupling mechanism between optical and mechanical degrees of freedom. There has been a lot of interest in the creation of quantum correlations in macroscopic mechanical systems, achieved using optomechanical models. A typical optomechanical system driven by a laser is shown in *Figure* 4.

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On the one hand, there is the highly sensitive optical detection of small forces, displacements, masses, and accelerations. On the other hand, cavity quantum optomechanics promises to manipulate and detect mechanical motion in the quantum regime using light, creating nonclassical states of light and mechanical motion. These tools form the basis for applications in quantum information processing, where optomechanical devices could serve as coherent light-matter interfaces, for example, to interconvert information stored in solid-state qubits into flying photonic qubits. At the same time, it offers a route towards fundamental tests of quantum mechanics in a hitherto unaccessible parameter regime of size and mass.

6. PT Symmetry

The concept of parity-time (PT) symmetry has played a crucial role in extending quantum mechanics to the non-Hermitian domain. A non-Hermitian Hamiltonian can also have real eigenvalues if it possess PT symmetry. To be precise, the Hamiltonian $\hat{H}$ with $\hat{H} \neq \hat{H}^\dagger$, where the symbol † stands for Hermitian conjugation, can have a real spectrum of eigenvalues if $(\hat{P}\hat{T})\hat{H} = \hat{H}(\hat{P}\hat{T})$, where $\hat{P}$ and $\hat{T}$ are the Parity and Time-reversal operators, respectively. They have the following actions on the position ($\hat{x}$) and momentum ($\hat{p}$): $\hat{P}\hat{x}\hat{P} = -\hat{x}$, $\hat{P}\hat{p}\hat{P} = -\hat{p}$; $\hat{T}\hat{p}\hat{T} = -\hat{p}$, $\hat{T}\hat{x}\hat{T} = \hat{x}$ and $\hat{T}\hat{i}\hat{T} = -\hat{i}$. Therefore, for a general Hamiltonian $\hat{H} = \hat{p}^2/2m + \hat{V}(\hat{x})$ to be PT symmetric, the potential term must satisfy the condition $\hat{V}(\hat{x}) = \hat{V}^*(-\hat{x})$. Although the idea of PT symmetry was introduced in quantum mechanics in [16], the importance of the phenomenon has been realized recently [17]. Equivalence of a quantum system possessing PT symmetry to a quantum system having Hermitian Hamiltonian was shown in [18].

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A new direction, in the application of PT symmetry, could be the study of non-Hermitian effects in small-scale devices as well as in atomic and molecular systems, where quantum processes are known to play a significant role. These include, for instance, driven atomic condensates in cavities, artificial atoms, or hybrid quantum systems in cavity quantum electrodynamics as well as coupled optomechanical resonators with gain and loss, where effects such as phonon lasing near exceptional points could be explored. Initial theoretical studies in this direction shows that the presence of quantum noise leads to significantly different physics as compared to that expected from semiclassical approaches. Novel phases with preserved or *weakly* broken PT symmetry appear. Such interactions could in principle also appear in other contexts of quantum optics, such as the prototypical case of an atom interacting with the mode of a light field in an open system.

[19] discusses a system that was realized whose dynamics is governed by a PT Hamiltonian. Many optomechanical properties have been investigated, such as the cavity optomechanical properties underlying the phonon lasing action, PT-symmetric chaos, cooling of a mechanical oscillator, cavity assisted metrology, optomechanically-induced-transparency (OMIT), and optomechanically induced absorption (OIA).

7. Quasiprobability Distributions and Tomography

7.1 *Quasiprobability Distributions*

A very useful concept in the analysis of the dynamics of classical systems is the notion of phase space, i.e., taking into account both the position and momentum. A straightforward extension of this to the realm of quantum mechanics is, however, foiled due to the uncertainty principle. Despite this, it is possible to construct quasiprobability distributions (QDs) for quantum mechanical systems, in analogy with their classical counterparts. These QDs are very useful in that they provide a quantum-classical correspondence, and facilitate the calculation of quantum mechanical averages in close analogy to classical phase space averages.

Nevertheless, the QDs are not probability distributions as they can take negative values as well, a feature that could be used for the identification of quantumness in a system.

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The first such QD was developed by Wigner, resulting in the epithet Wigner function (W) [20]. Another very well-known QD is the P function, whose development was a precursor to the evolution of the field of quantum optics. This was originally developed from the possibility of expressing any state of the radiation field in terms of a diagonal sum over the coherent states [3, 4]. The P

function can become singular for quantum states, a feature that promoted the development of other QDs such as the Q function, as well as, further highlighted the use of the W function, which does not have this feature.

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A nonclassical state can be used to perform tasks that are classically impossible. This fact motivated many studies on nonclassical states, such as studies on squeezed, antibunched, and entangled states. The interest in nonclassical states has increased with the advent of quantum information processing where several applications of nonclassical states have been reported. The fields of quantum optics and information have matured to the point where intense experimental investigations are being undertaken. Both from the fundamental perspective as well as from the viewpoint of practical realizations, it is imperative to study the evolution of the system of interest taking into account the effect of its ambient environment. This is achieved systematically using the formalism of Open Quantum Systems [7].

7.2 *Tomography*

There is no general prescription for direct experimental measurement of the quasidistribution functions, such as Wigner function [21]. In general, to detect the nonclassicality in a system the Wigner function is obtained either by photon counting or from experimentally measured tomograms [21]. Reconstruction of a quantum state from experimentally measured values is of prime interest for both quantum computation and communication. The tomogram is one such candidate as it is experimentally measurable and is obtained as a probability distribution. Further, the quantum state tomography has its applications in quantum cryptography.

Specifically, in [22], it is strongly established that tomography and spectroscopy can be interpreted as dual forms of quantum computation. From the experimental perspective, a quantum state always interacts with its surroundings. Hence, it is important to consider the evolution of the tomogram after taking into account the interaction of the quantum state with its environment.

8. Topological Photonics

Topological phases in condensed matter that usually arise out of Berry phase effect during adiabatic evolution of states have taken the centre-stage of research in the condensed matter community for quite some time now. Interesting findings such as topological insulators, where conducting edge/surface states appear in an otherwise bulk-insulating system or Weyl semimetals, where topologically robust Weyl charges, analogous to magnetic monopoles of the Berry curvature of Bloch bands, appear in pairs within its bulk, are currently being investigated with intense vigour.

Over the last decade, there has been a very exciting new development in quantum optics with roots in condensed matter physics, in particular, topological insulators and quantum Hall effects. This is the field of topological photonics [23, 24], where externally provided photons in photonic crystals can induce surprising topological effects. As topological insulators are rare among solid-state materials, suitably designed electromagnetic media (metamaterials) can demonstrate a photonic analog of a topological insulator. They provide topologically non-trivial photonic states, similar to those that have been identified for condensed-matter topological insulators. The interfaces of these metacrystals support helical edge states, robust against disorders.

Over the last decade, there has been a very exciting new development in quantum optics with roots in condensed matter physics, in particular, topological insulators and quantum Hall effects.

Topology is the study of geometrical conserved quantities, and its use in the context of optics allows the creation of new states of light with interesting properties. Thus, for example, one could have robust unidirectional waveguides allowing light to propagate around defects without back-reflection. This also provides opportunities to realize and exploit topological effects in new ways. The practical implications of topological photonics include the possibility of applications to quantum information processing and topological quantum computing. Another application could be topological lasers, the study of laser oscillation in topological systems.

To summarize, we have attempted to give a brief overview of the recent developments in the field of quantum optics. Efforts have been made to connect the modern developments with the roots of the subject. The subject has seen enormous progress in various directions and is believed to provide the testbed for exploring some of the fundamental problems of physics.

Suggested Reading

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