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From quantum optics to quantum communications

Aspects quantiques des communications optiques

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Abstract

We review the possible roles of quantum optics and quantum information methods for future developments of optical telecommunications. ***To cite this article: I. Abram, P. Grangier, C. R. Physique 4 (2003).***

Résumé

Nous passons en revue le rôle potentiel des methodes de l'optique quantique et de l'information quantique dans les développements futurs des télécommunications optiques. ***Pour citer cet article : I. Abram, P. Grangier, C. R. Physique 4 (2003).***

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Mots-clés : Optique quantique ; Optique non linéaire ; Principe d'incertitude de Heisenberg ; Fluctuations du vide ; Bruit quantique ; Superposition quantique ; Intrication ; Bruit de grenaille ; Bruit quantique comprimé ; Force de Casimir ; Émission paramétrique ; Mesure quantiquement destructive ; Amplification sans bruit ; Branchement sans bruit ; Émission spontanée ; Bande interdite photonique ; Distribution quantique de les cryptographique ; Téléportation quantique

1. Introduction

The quest for faster and more energy-efficient technologies for information processing and communication has led to a constant reduction in the energy content of signals, over the past sixty years. Thus, as the capacity of optical transmission systems advances beyond the multi-terabit range, we can expect the energy per bit to become much less than a femtojoule. In parallel, the size of components may reach dimensions as small as a few nanometers, according to the trend towards miniaturization expressed by Moore's law.

Quantum optics aims at understanding and mastering the laws that govern the behavior of light and of optical components at very weak intensities and at very short distances. As we shall see below, quantum behavior is already apparent in long-haul amplified systems with large photon numbers, as well as in microwave engineering when quantum fluctuations dominate over thermal noise. Presently, the transmission of information through signals that are fully governed by quantum laws is not yet

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implemented in practical optical communications and information processing systems. Nevertheless, basic research in this field permits us to anticipate the directions in which optical communications might evolve, as miniaturization proceeds and quantum phenomena become more and more prominent.

At present, the large number of photons that compose an optical signal, and the large number of atoms that constitute an electronic or optoelectronic component, produce a statistical averaging effect. In most cases, this erases the quantum behavior of the individual particles, and gives rise to the classical deterministic properties with which we are familiar in 'large' objects. Thanks to classical physics, signal coding and information processing are achieved by exploiting the well-defined states of signals consisting of several million photons, and the deterministic interactions between objects whose size can be as small as a fraction of a micrometer. However, as the energy content of signals and the size of components are reduced, the averaging process becomes incomplete. Then deviations from classical deterministic physics become apparent, first as unwanted *quantum noise*, and then gradually moving into a full quantum behaviour.

The first appearance of quantum laws for weak optical signals is related to *Heisenberg's uncertainty principle* which manifests itself, in the course of signal processing, as a noise that scrambles the initial value encoded on the signal. Nevertheless, it is possible to keep or restore the signal into its initial state by developing *quantum noise suppression* techniques. A fundamental difference between classical and quantum noise, however, is that the minimal amount of noise that is imposed by the uncertainty principle cannot be erased like classical noise; it can, however, be modified or displaced, and thus circumvented. Since many of the fundamental sources of noise in present-day communications are of quantum origin, and since the technical sources of noise are being progressively eliminated, the different strategies for reducing quantum noise developed in quantum optics [1,2] may become applicable to optical communications in a relatively near future. A good understanding of quantum noise also helps to eliminate 'excess noise' of classical origin, due to technical imperfections, electronic or thermal fluctuations – as this kind of noise is less and less tolerable when system performance increases.

Upon further miniaturization, for instance when the information-carrying signals are composed of single photons, the familiar classical behavior of light can be completely absent and the manifestations of quantum behavior will dominate. Beyond the manifestations of *uncertainty*, two additional quantum phenomena, namely *superposition* and *entanglement*, have proved to be key concepts of quantum optics that are relevant for information processing and communication. Superposition permits an information-carrying signal to assume both binary values at the same time, while entanglement makes that information into a global property of a delocalized system, rather than a local property of its parts. Thus, as the trend to miniaturization of signals and components proceeds and their classical deterministic behavior progressively disappears, it may become necessary – or at least useful – to move to the concepts of quantum information theory [3]. This will require adapting the procedures for coding, transmitting or processing information to the quantum behavior of the *nanosignals* and *nanoobjects* that carry or handle this information.

In this paper, we shall describe the contribution that quantum optics may bring to optical communications, by examining the physics behind the three concepts of uncertainty, superposition, and entanglement, the possibility of direct application of these concepts to optical communications, and the spinoffs they have generated. The paper is organized as follows. In Section 2, we will see how *quantum uncertainty* can introduce unwanted noise in light sources, propagation, amplification and processing. Then we will describe various techniques that can be used to circumvent this noise, using either *optical non-linearities* (Section 3) or *cavity quantum electrodynamics* (Section 4). In Section 5, we will enter briefly into the novel domain of *quantum information*, in which quantum properties are exploited as a resource rather act as an unwanted source of noise. In that section, we start by a describing the basic principles and the state-of-the-art of *quantum key distribution* techniques, and then, in the last subsections, we present some perspectives towards *entanglement-based quantum communications*.

2. Noise due to quantum uncertainty

2.1. Introduction

In quantum mechanics, Heisenberg's uncertainty principle forbids two non-commuting observables to both take a definite value simultaneously. For instance, in a state of the electromagnetic field in which the energy is well-defined, the field amplitude cannot take a definite value. This is true, in particular, in the electromagnetic vacuum (i.e., in the total absence of light) where the measurable energy is strictly zero. Because of the uncertainty principle, however, the field amplitude cannot also take the value of zero but must fluctuate randomly. These *vacuum fluctuations* have very important consequences for optical telecommunications, as they constitute a fundamental source of noise that contaminates an optical signal at every stage of its life, its generation, propagation, distribution, or amplification. Since the subject of the quantum noise limitations of optical communications systems is treated more extensively in another article of this issue [4], we review here very briefly a few well-known examples of the direct manifestations of vacuum fluctuations in the different functionalities of a telecommunications system.

2.2. Quantum noise in signal generation

In signal generation, the vacuum fluctuations manifest themselves in two distinct ways: (a) in the existence of *spontaneous emission* in the amplifiers and lasers used in optical communications; and (b) in the *shot noise* of the optical signals.

Spontaneous emission is a process whereby the energy stored in the active medium of the laser is given off as light, with the emission of photons being triggered by the vacuum fluctuations, at random time intervals. Spontaneous emission is an indispensable ingredient in the operation of lasers, as it is this phenomenon that provides the first photon that triggers the stimulated emission, characteristic of the laser output, which is coherent and directional. However, the light that is emitted spontaneously is incoherent and omnidirectional and thus, apart from triggering stimulated emission, it represents an energy loss mechanism, and a source of excess phase and amplitude noise both for optical amplifiers and lasers.

Shot noise is caused by the granularity of energy flow due to the existence of light quanta, the photons. An ideal laser emits *coherent light*, that is a wave with a relatively well-defined amplitude and phase, whereas a photodiode detects energy, that is the number of photons incident on it. In other words, the process of coherent light generation and the process of light detection deal with two different variables (amplitude and photon number), which according to quantum mechanics are not compatible. Thus, in measuring the energy of a perfect coherent laser pulse, the detector will measure a fluctuating number of photons, with *Poisson statistics*. Shot noise is not a technical shortcoming of the detector but is another aspect of the phenomenon of vacuum fluctuations. One of the consequences of shot noise is to set a minimum energy for error-free detection, since the Poisson statistics require the detection of a few tens of photons to obtain an acceptable signal-to-noise ratio.

2.3. Quantum noise in distribution and propagation

Following the life history of an optical signal after it is generated, it generally propagates in a transmission system. Optical transmission systems are generally complex networks that include nodes and branching points in which the signal is divided into two or more channels. Upon branching, the relative fluctuations of the photon number of the emerging pulses are increased with respect to those of the incoming pulses, giving rise to partition noise. The origin of partition noise can be understood in quantum optics by considering the simplest model for a branching device that of a beamsplitter, that is a mirror with partial transmission T and reflectivity $R = 1 - T$. It is a device with two output ports (labeled 3 and 4 on Fig. 1) but also with two input ports (labeled 1 and 2). Translating the fact that an electromagnetic field in port 1 is partially transmitted into port 3 and partially reflected into port 4, the electric field amplitudes at the four ports can be linked by a unitary input–output transformation of the form

$$a_1 = \sqrt{T}\, a_3 - \sqrt{1-T}\, a_4, \qquad a_2 = \sqrt{1-T}\, a_3 + \sqrt{T}\, a_4 \tag{1}$$

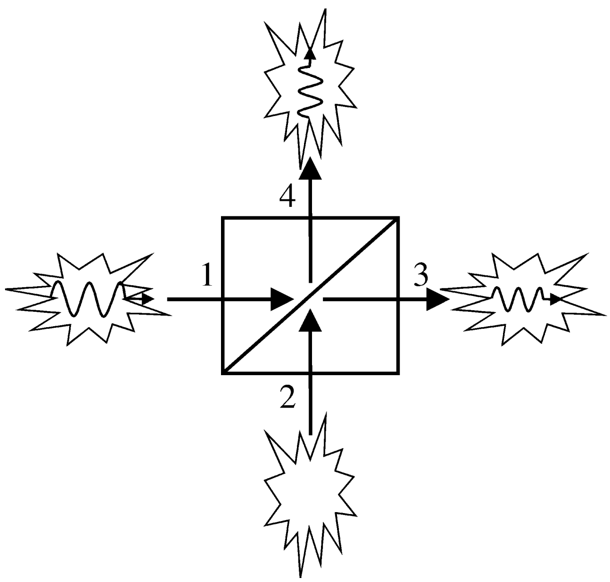

Fig. 1. Generalized four-port device representing the quantum structure of a distribution node or an amplifier. Input port 1 receives the signal which is channeled, after splitting or amplification, to the output ports 3 and 4. Input port 2 receives vacuum fluctuations (quantum noise) which is also channeled to the output ports after mixing with the signal.

which can also be written as

$$a_3 = \sqrt{T}\,a_1 + \sqrt{1-T}\,a_2, \qquad a_4 = -\sqrt{1-T}\,a_1 + \sqrt{T}\,a_2. \tag{2}$$

These equations indicate that the outputs at ports 3 and 4 result from a mixing of the incoming signals in ports 1 and 2. It is interesting to note that Eqs. (1) and (2) retain exactly the same form when written with quantum field operators rather than classical field amplitudes. This actually means that when the beamsplitter is used as a branching device, i.e., when a signal is introduced into port 1, then the 'empty' port 2 actually carries the vacuum state of the electromagnetic field. Splitting the incoming signal then corresponds to an electromagnetic interference process that mixes the signal field in port 1 and the vacuum fluctuations in port 2. The two emerging beams then, in ports 3 in 4, inherit an amplitude derived from the amplitude of the incoming signal but also inherit a noise due to the vacuum fluctuations that enter through the second input port. It should be noted that the four-port model for a branching device is imposed by the requirement that the input and output fields be related by a unitary transformation, and is independent of the geometry the device. Thus, even a 3 dB fiber Y-coupler, commonly used in fiber networks, whose apparent geometry displays only three ports, is actually a four-port device (the fourth port corresponding to refractive leakage modes) that mixes the signal with additional vacuum fluctuations, thus introducing partition noise. Cascading of branching points produces an accumulation of partition noise and this imposes limitations on the network architecture with respect to the number of nodes or read-out ports.

In the course of its propagation in an optical fiber, an optical signal is also subject to attenuation due to the residual absorption and the Rayleigh scattering of silica. Viewed from the perspective of quantum optics, this process continually increases the relative noise of the signal by mixing it with vacuum fluctuations. This can be seen by considering the fiber as a 'distributed four-port device' that gradually divides the energy of the signal between the propagation channel and the loss channel, thus adding partition noise.

2.4. *Quantum noise in amplification*

When a light pulse is too weak to be detected because of attenuation, energy can be injected into it through optical amplification. This increase of the pulse energy, however, is also accompanied by an increase in its noise degrading the signal to noise ratio by 3 dB (this is an asymptotic value that is reached for large gain). The origin and the fundamental nature of this excess noise (Fig. 2) also can be viewed in quantum optics as a consequence of the requirement that the input and output fields be related by a unitary transformation. Considering formally the amplifier as an 'inverse attenuator', with a transmission coefficient larger than 1 (that is, it corresponds to a gain), the input–output relation can be written as

$$a_3 = \sqrt{G}\,a_1 + \sqrt{G-1}\,a_2^*, \tag{3}$$

where the complex conjugate of the field amplitude in port 2 is used, to account for the phase change introduced by the square root when T is larger than 1. The structure of this equation is also the same quantum mechanically, by changing the complex conjugate into the hermitian conjugate of the corresponding field operator.

In Eq. (3), port 2 corresponds to a second 'input port' of the amplifier that is normally empty, i.e., it contains only vacuum fluctuations. Thus, according to this equation, the excess noise of a linear amplifier comes from its quantum mechanical structure which requires that, in addition to the channel in which amplification occurs, the device must include at least one additional channel, such as the non-lasing modes of the laser, into which the vacuum fluctuations produce spontaneous emission in a random way. The spontaneous emission events deplete randomly the energy stored in the amplifier and thus cause fluctuations of the gain which, in turn, produce noise in the amplified signal. It should be noticed that the corresponding noise is associated with photons that are really added to the signal, while this was not the case in Eq. (2). This is why the amplifier noise can also be interpreted as a noise due to amplified spontaneous emission. Obviously, this noise limits the number of amplifiers that can be cascaded, and thus imposes a constraint on total length of a transmission link and on the architecture of optical networks.

In lasers, Eq. (3) also holds for a single pass through the amplifying medium, but due to the cavity feedback the overall dynamics is quite different. This is due to the *gain saturation* mechanism, that basically damps the intensity fluctuations, down to a value that is simply shot-noise for a Poissonian laser pumping mechanism. On the other hand, there is no restoring mechanism for phase fluctuations, giving rise to the well-known phase diffusion, associated with the Schawlow–Townes linewidth. In addition, there are many other mechanisms that add excess noise in lasers, e.g., mode competition [5], phase-amplitude coupling in the amplifying medium (Henry parameter [6]), and loss-induced coupling between different laser modes (Petermann factor [7,8]).

2.5. *Quantum noise in opto-mechanical components*

The vacuum fluctuations give rise also to mechanical effects. A cavity composed of two plane parallel metallic mirrors cannot sustain any radiation whose wavelength is longer than twice the distance between the mirrors. This is true both for the

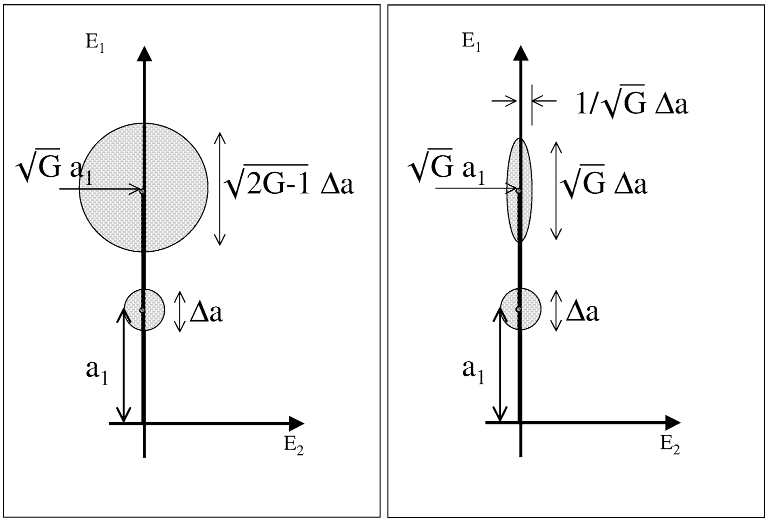

Fig. 2. Quantum noise in amplification. (a) In a linear amplifier, both quadratures E_1 and E_2 are equally amplified. Thus, upon amplification, the noise of both quadratures is amplified and mixed, so that an input signal with minimal quantum noise Δa (represented by a spot at the tip of the signal vector) ends up with noise $\sqrt{2G-1}$ larger. (b) In a phase-sensitive amplifier, quadrature E_1 is amplified while quadrature E_2 is deamplified. Upon amplification the noise of the two quadratures is not mixed, so that in each quadrature the noise is amplified (or deamplified) by the same factor as the corresponding signal, resulting in no change in the signal-to-noise ratio.

energy carrying oscillations of the electromagnetic field and for its vacuum fluctuations. Thus, when two metallic mirrors are spaced by less than a micrometer, the exclusion of the vacuum fluctuations from that space induces an attractive force between the two mirrors, called the *Casimir force*. This is analogous to the effective attraction between two boats sailing next to each other in a choppy sea. In the space between the two boats, the sea is relatively calm and the external waves push the boats one against the other. The Casimir force was recently identified [9] in Micro-Opto-Electro-Mechanical devices (MOEMs) that have been developed for optical switching, such as pivoting micro-mirrors or adjustable frequency filters. Clearly, it is important that mechanical manifestation of the vacuum fluctuations be controlled especially in view of the advancement of miniaturization.

3. Quantum noise management

3.1. Introduction

The manifestations of vacuum fluctuations impose limitations on the fidelity of a transmission system which, at present, are still masked by technical limitations. However, as the continuous improvement of electronic and optoelectronic components permits the progressive elimination of noise due to their technical imperfections, quantum noise could soon become the limiting factor for the performance of optical communications systems. This stage has already been reached for the case of *Erbium doped optical fiber amplifiers* (EDFA) for which the signal-to-noise degradation upon amplification is of the order of 4 dB while the quantum limit due to the vacuum fluctuations stands at 3 dB, and the 1 dB penalty is due to input coupling loss or excess loss from the components used in commercial modules.

The research activity in quantum optics over the last 15 years has focused on the control and the reduction of vacuum fluctuations and of quantum noise in optical signals by developing two types of generic technologies: *nonlinear optics* and *cavity quantum electrodynamics*.

3.2. Nonlinear optics

Nonlinear optics is based on the use of special materials whose optical properties depend on the intensity of incident light. When two light waves propagate through such a medium, they interact with each other and this interaction imparts quantum correlations at the level of their quantum fluctuations. These correlations can then be exploited to reduce quantum noise in optical components and thus circumvent the *standard quantum limit* due to the vacuum fluctuations in the processing of optical signals.

In this context, a very important notion is the one of *quadrature components*, that can be seen as the two parts of the electric field that are $\pi/2$ out of phase (in other terms, the 'sine' and 'cosine' parts of the electric field). In a quantum approach, the corresponding observables do not commute, and are constrained by the *Heisenberg relations*. A central idea in quantum noise management is to arrange so that only one of these two quadrature components carries the signal of interest. Then, this *quadrature of interest* (QI) may undergo an essentially noise-free evolution, provided that the unavoidable quantum noise is dumped into the other quadrature component, that we will call *quantum dump* (QD), in order to preserve the Heisenberg uncertainty relation. This basic idea is used, e.g., in *squeezed light generation* [1], *quantum non-demolition measurements* [2], and many other techniques, that are usually denoted as 'phase-dependent' processes (or, equivalently, 'quadrature-dependent'). A very interesting feature is that most nonlinear optical processes exhibit the kind of phase-dependence that is required here. Among them, two phenomena have been implemented more particularly in quantum noise reduction.

The first one, *parametric downconversion*, consists of a process in which the photons of an incident light beam (called 'pump beam') undergo fission to produce each two twin photons of half the energy. At high pump intensities, a parametric downconverter turns into a parametric amplifier, as we shall see below. The second nonlinear optical process is *nonlinear refraction*, whereby a propagating laser pulse modifies momentarily the refractive index of the medium, and thus can change its own speed of propagation (self-phase modulation – SPM) or the speed of another co-propagating beam (cross-phase modulation – XPM). Throughout the late 1980s and the early 1990s, a large number of experimental papers appeared in the literature in which these two phenomena were used to reduce quantum noise in many different situations. We shall review here briefly the reduction of quantum noise in two important functionalities of optical communications: *noiseless amplification* and *noiseless branching*.

3.3. Noiseless amplification

In parametric downconversion, the emission of photon pairs can be used to amplify an incoming beam, through a process known as *parametric amplification* whose distinctive feature is that it possesses an internal phase reference determined by the pump beam. This provides the required phase-dependence introduced above. If the incoming field is in-phase with the internal reference it gets amplified, while if it is $\pi/2$ out of phase it gets de-amplified. Let us define $X^{\mathrm{QI}} = a\,\mathrm{e}^{\mathrm{i}\phi} + a^*\,\mathrm{e}^{-\mathrm{i}\phi}$, and $X^{\mathrm{QD}} = \mathrm{i}a\,\mathrm{e}^{\mathrm{i}\phi} - \mathrm{i}a^*\,\mathrm{e}^{-\mathrm{i}\phi}$, where ϕ is chosen to select the appropriate quadrature of interest QI. Parametric amplification is then described by the equations:

$$X_{\mathrm{out}}^{\mathrm{QI}} = g X_{\mathrm{in}}^{\mathrm{QI}}, \qquad X_{\mathrm{out}}^{\mathrm{QD}} = \frac{1}{g} X_{\mathrm{in}}^{\mathrm{QD}}. \tag{4}$$

The corresponding input–output relation for the field amplitude in a parametric amplifier, analogous to that of Eq. 3, can then be written as

$$a_{\mathrm{out}} = \sqrt{G}\,a_{\mathrm{in}} + \sqrt{G-1}\,a_{\mathrm{in}}^*, \tag{5}$$

where $G = (g^2+1)^2/(4g^2)$. Comparing with Eq. (3), it appears that a phase-dependant parametric amplifier is actually a *degenerate* four-port device, that has turned into a two-port device because the extra noise mode is now the conjugate of the input mode. So there is no added noise at all, but simply the QI, which carries the useful signal, is amplified, while the QD, which carries only noise, is deamplified [10]. Parametric amplifiers can, therefore, be noiseless for the QI (noise figure of 0 dB at large gain), in contrast to classical optical amplifiers, such as EDFAs, which degrade the signal-to-noise ratio by 3 dB because of the vacuum fluctuations.

The quantum correlations produced by nonlinear refraction can also lead to noiseless amplification. A well-known example is that of the noiseless amplification of optical fiber solitons. The physics and the perspectives of solitons in optical telecommunications are discussed more extensively in another article in this issue [11]. Here, it is sufficient to point out that solitons are stable pulses of light, whose stability results from the compensation of the chromatic dispersion of the fiber by its nonlinear index of refraction. They are nevertheless subject to attenuation in the fiber, so that they need to be amplified periodically (typically, at distances of a few tens of kilometers) if they are to be used in long-haul communications. Use of conventional fiber amplifiers, however, introduces noise in the form of random fluctuations in the central wavelength of the solitons, which in turn produces a jitter in their timing, because of the chromatic dispersion of the fiber. Accumulation of this timing noise over distances of a few thousand kilometers compromises the fidelity the transmission. The timing noise can be prevented through the use of wavelength-selective amplifiers that can be made essentially by adding a narrow-band wavelength filter immediately downstream from an Erbium doped fiber amplifier EDFA. The reduction of the amplifier bandwidth limits the excursions of the soliton wavelength fluctuations and thus prevents the accumulation of timing noise [12]. This technique reduces the amplification noise by exploiting essentially the quantum correlations that the nonlinear refraction of the fiber produces among the different wavelength components of the soliton [13]. Amplification occurs only in the wavelength channels that carry the soliton signal and not in those that introduce vacuum fluctuations.

3.4. Sub-shot-noise lasers

The quantum analysis of the laser dynamics show that the intensity noise in a laser far above threshold is ultimately due to the fluctuations of the pumping mechanism [14,15]. Therefore, a laser with reduced pumping noise, often called *quiet pumping*, should emit *sub-shot noise light*. Quiet pumping is very easily obtained in semiconductor lasers (laser diodes), simply by using a high-impedance current source. This idea was demonstrated initially by Yamamoto [15,16], and has given rise to many studies since then.

Though the original idea is basically correct, the actual noise behaviour is significantly complicated by the fact that lasers are inherently multimode systems: even a ‘single-mode laser’ contains spontaneous emission in non-lasing modes, and this must be take into account for a full understanding of the noise behaviour [5,8]. For example, the pointing instability of a nominally single mode laser has been shown to result from the homodyne beating of the fundamental TEM_{00} with the first non-lasing mode TEM_{01}, which carries only spontaneous emission noise [17]. Presently, noise reductions of about 2–3 dB below shot noise can be observed routinely at room temperature. Specifically designed or selected laser diodes, working at low temperature, emit light with fluctuations 5–6 dB below shot noise. These results are quite significant for future developments, even if at present the application niche for sub-shot-lasers is rather small, because most optical telecommunications systems are designed so that the initial laser noise is not a limiting factor.

3.5. Noiseless branching

Nonlinear optical processes can also be used to achieve noiseless branching in which the signal-to-noise ratio of the two output channels is identical to that of the input channel, while the two output signals are the same, including even their quantum fluctuations that are thus strongly correlated. As before, this is obtained for the QI only, and ‘Heisenberg noise’ has to be dumped in the QD. This is achieved by implementing the principles of *quantum non-demolition* (QND) optical measurements whereby the modulation and the noise of the QI are measured without the beam being destroyed, as would have been the case if the measurement were done by a traditional photoelectric detector. The QND measurement is achieved by transferring the modulation and the noise of the signal beam onto a ‘meter’ beam, so that the two output channels of the QND device (the transmitted and the meter channels) carry two identical copies of the incoming information, down to the level of the quantum fluctuations. QND thus gives rise to noiseless branching nodes that could permit the development of distribution networks bringing into play a very large number of cascaded nodes, without any constraints on their architecture, in contrast to classical Y-couplers which introduce partition noise and degrade the signal-to-noise ratio at every branching point.

A relatively simple QND device can be implemented by introducing a medium with a nonlinear refractive index in one arm of an interferometer [2]. The intensity modulation of the signal beam (including its shot noise) produces a modulation of refractive index of the medium, because of the nonlinearity. As the co-propagating meter beam experiences the index modulation, it undergoes a phase modulation which in turn is converted into an intensity modulation by the interferometer. At the output of the interferometer, both the transmitted and the meter beams have identical intensity modulations, down to the level of the photon fluctuations. An amplifying QND device can be obtained by combining two parametric amplifiers with a beamsplitter, so that the two input ports of the beamsplitter receive the parametrically amplified signal on one side, and the parametrically de-amplified (or squeezed) vacuum fluctuations on the other side [2,10]. In this way, the beamsplitter mixes the amplified signal with *squeezed partition noise,* and thus the two output ports receive two identical amplified copies of the QI.

3.6. State of the art

The experimental research of the last 15 years has concentrated on demonstrating the principles of the suppression of quantum noise by the use of an optical nonlinearity and has given a strong the impetus to the study of the noise limitations of present-day optical systems. Many of these demonstrations of principle [2] have relied on complicated laboratory setups that cannot be easily implemented in an operational optical network, but more recently the non-linearity of optical fibers has been put into use for quantum noise control. After the noiseless amplification of solitons, it has also been shown that optical fibers can be used to produce strongly squeezed light [18], and to achieve QND measurements [19].

In the not too distant future, as the bit rate and transmission distance of optical systems increases, limitations will arise from the accumulation of quantum and nonlinear noise, as discussed in another article in this issue [4]. However, as the research on quantum noise reduction has demonstrated, adequate strategies based on optical nonlinearities can be used to push the performance of optical communications well beyond the standard quantum limits.

4. Cavity Quantum Electrodynamics

4.1. Introduction

In Cavity Quantum Electrodynamics [20], the electromagnetic field is confined in a small region of space, with dimensions of the order of the optical wavelength, bounded by mirrors. Because of the electromagnetic interference phenomena in such a cavity, the spatial distribution of the radiation and of the vacuum fluctuations is modified and this can change the strength of the interaction between light and matter inside the cavity, resulting in either an inhibition [21] or an increase [22] of spontaneous emission. Thanks the technological development of microstructures over the past 10 years it has been possible to fabricate such cavities in semiconductors and study the control of the vacuum fluctuations and the light-matter interaction in these materials [23]. The extension of the field of Cavity Quantum Electrodynamics to room temperature semiconductors opens the way to its application to optoelectronic components, in a similar way as in the 1960s the extension of laser physics to semiconductors lead to the development of the key components on which optical communications are now based.

4.2. Control of spontaneous emission

An optical cavity bounded by two metallic mirrors spaced by a few hundred nanometers displays a cutoff frequency, such that visible or infrared radiation is completely excluded from the cavity. Below the cutoff frequency the cavity is ‘absolutely dark’ with a complete exclusion of both photons and vacuum fluctuations at the forbidden frequencies. An important consequence of this elimination of vacuum fluctuations is that the spontaneous emission of an active medium placed in the cavity is inhibited [24] and can therefore be controlled. Such a control would permit the design of lasers in which spontaneous emission would not be omnidirectional but would be channeled in the useful mode in order to trigger stimulated emission as soon as the first photon appears, giving rise to extremely efficient components with a very broad bandpass, low noise, and low thermal dissipation. This would permit the pursuit of miniaturization and the integration of light sources to produce photonic circuits which would operate on weak optical signals in a manner analogous to that of microelectronics.

The effort for eliminating the vacuum fluctuations produced an important new idea in the late 1980s, that of structures with a *photonic bandgap* [25]. These are three-dimensional structures that present a periodic variation of the refractive index in the three directions of space, for example by fabricating a lattice of holes (corresponding to the refractive index of air) in a material of high refractive index. In such structures, the electromagnetic field and its vacuum fluctuations are completely excluded within a certain frequency band (called a photonic bandgap) whose central frequency and bandwidth are determined respectively by the periodicity of the structure and the refractive index contrast.

4.3. Spinoffs in guided-wave optics

In addition to their interest in Cavity Quantum Electrodynamics, photonic bandgap structures have found novel applications in planar waveguides and in optical fibers, as high-performance cladding materials. The extraordinary properties of photonic-clad waveguides come from the fact that the photonic structure excludes completely the field from the cladding and thus confines it very strongly in the core of the waveguide [26].

In particular, as discussed more extensively in another article in this issue [27], different types of fibers with photonic confinement have been fabricated by structuring their cladding through longitudinal air channels disposed in a periodic daisy-like pattern around the core. The core itself can be made with high refractive index material or even left empty. Such fibers have proved to be single-mode for all useful wavelengths (in the visible or near infrared) with dispersion characteristics that can be tailored through the design of the pattern of air channels. In addition, an appropriate air channel pattern can increase confinement of the mode at the core by more than one order of magnitude with respect to classical refractive fibers. This feature can greatly increase the nonlinearity of the fiber if its core is made of silica, whereas it can reduce the nonlinearity and the signal attenuation when the core is empty. Photonic fibers open thus the way to the engineering of the chromatic dispersion, the nonlinearity, and the attenuation in fibers. Given the important role of non-linearities for quantum noise control, this should permit to push further away the limitations due to noise accumulation, and provide the potential for greatly increasing the capacity of optical transmission systems.

5. Beyond quantum noise

5.1. Introduction

In the discussion above, the quantum properties of light and matter appear essentially as a nuisance, creating troublesome noise that must be circumvented. But when one goes further into the quantum domain, down to single photons and atoms, all physical properties acquire a quantum character, and cannot be considered as noise any more. This quantum character is still most often seen as a set of constraining rules, that leave little freedom for useful actions. But over the past few years, thanks to the development of the field of quantum information, it has be realized that these rules can be turned into an advantage, opening new possibilities based on quantum physics that would not have been accessible with classical physics. Here, we will consider very briefly some of the communication aspects of quantum information, leaving aside other important developments, such as *quantum computing*.

5.2. Exploiting quantum superpositions of single photons

Since single photon detectors are readily available, trains of single photons can be used to code and to transmit information. Encoding binary information on single photons is relatively easy, for instance by establishing a correspondence between the bits 0 and 1 and two orthogonal linear polarization directions. Let us consider briefly information encoded in the $\hat{x}/\hat{y}$ basis (with $\hat{z}$ being the propagation direction) or, alternatively, in the $\hat{u}/\hat{v}$ basis, rotated by 45 degrees with respect to $\hat{x}/\hat{y}$. Because the $\hat{u}$ and $\hat{v}$ axes are linear combinations of $\hat{x}$ and $\hat{y}$, a photon polarized along, say, $\hat{u}$ corresponds actually to a superposition of the two polarizations along $\hat{x}$ and $\hat{y}$. This means that information encoded in the $\hat{x}/\hat{y}$ basis is not compatible in the quantum sense with information in the $\hat{u}/\hat{v}$ basis: a definite value encoded in one basis set, gives rise to an uncertainty in the other. At the same time, this feature illustrates the fact that a polarized photon actually transmits a quantum bit, or qubit, which can assume both binary values at the same time, by a being in a superposition state.

In a practical optical link, in-line propagation losses produce a random decimation of the photon train, and sending information encoded on single photons is generally not compatible with the transmission of a predetermined message. On the other hand, the transmission of a random a number is not subject to this problem, since a random sequence of bits remains random after decimation of its elements. A very important use of a train of single photons is therefore the transmission of a *cryptographic key*, that can be used subsequently to code a message to be sent by conventional means. As we will see now, the security of this *quantum key distribution* (QKD) method can be guaranteed by the quantum laws.

5.3. Quantum key distribution: principle

The security of the transmission of a random key by a train of single photons is unconditionally guaranteed by a strategy based on the quantum theory of measurement and the use of superposition states [28,29]. This strategy permits the authorized users (Alice and Bob) to detect any attack in which an eavesdropper (Eve) tries to intercept the key, for instance by measuring each photon and then re-emitting it so as not to interrupt the transmission (Fig. 3). To insure security in the key distribution, two different non-orthogonal bases are alternatively and randomly used, so that a receiver who does not use the right basis set to read a particular bit will get erroneous results half of the time. For example, let us assume that the value 1 was coded by emitting a photon polarized along $\hat{x}$. If a measurement is carried out in the $\hat{u}/\hat{v}$ basis, the photon will be detected with equal probability to have a $\hat{u}$ or $\hat{v}$ polarization (thus interpreted as a 0 or a 1 with equal probability), producing an error half of the time. This is not a problem for Alice and Bob, because after the transmission is complete they can compare the basis sets used in emission and reception and discard the events in which the basis sets were different, which statistically account for half of the bits received. When the eavesdropper, however, uses the wrong basis set in the course of the transmission she has no way of comparing it with the basis set used in emission, and thus the errors in her reception mean that she retransmits erroneous data 25% of the time. The legitimate users can then detect the presence of the eavesdropper simply by comparing a random sample of the bits received to obtain the error rate of the transmission.

In practice, there are always transmission errors, and merely interrupting the transmission as soon as the error rate increases (possibly due to Eve, but possibly not), would not be of great use to Alice and Bob. Then a crucial point is that, as long as the error rate is not too large, the authorized parties are always able to extract from the exchanged quantum data a secret key that is *absolutely secure*. This is obtained by using provably secure classical algorithmic techniques, known as *privacy amplification*, that rely on suitably designed hashing functions. As a result, the effect of an increase in the error rate will be to decrease the rate of transmission of the secret key, but not its security. Obviously, only a finite error rate is tolerable, and in practice the secret key rate drops to zero when the error rate goes above a value close to 15%.

5.4. Quantum key distribution: state of the art

Presently several laboratories have demonstrated the quantum transmission of a cryptographic key for distances up to 50 kilometers and transmission rates on the order of a few kbits/s [30]. Such systems are now commercialized [31], and may be relevant for specialized economic niches that require absolute security over concentrated areas, like business or management centers, and are not too sensitive to cost and infrastructure complexity.

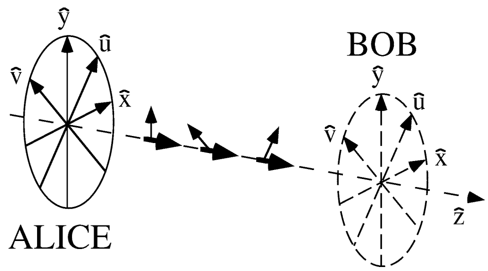

Fig. 3. Quantum key distribution between Alice and Bob using polarized photons. Alice sends single photons to Bob, choosing randomly any one of the four linear polarization $\hat{x}$, $\hat{y}$, $\hat{u}$, $\hat{v}$. Depending on his measurement, Bob may get the information either in the $\{\hat{x}, \hat{y}\}$ or the $\{\hat{u}, \hat{v}\}$ basis. Later he informs publicly Alice (and possibly Eve) about his basis choice, but obviously not about his result.

It should be noticed that at the present stage these QKD systems can guarantee the security of single photon transmission only against interception and not against the other security risks of communication, such as impersonation (emission or reception by an unauthorized user) or repudiation (reneging on what was actually sent). In other words, secure communication by single photon trains is possible only between two entities that have pre-established mutual confidence by classical means. There have been several attempts to use the principles of quantum mechanics also to establish confidence between remote partners, i.e., to implement the basic cryptographic functions that insure user identification, authentication, non-repudiation, message integrity, and signature. However, the main results in this domain are 'no-go' theorems, rather than positive results: for instance, *bit commitment*, which consists of recording a secret piece of information in an inalterable and verifiable way, has been shown to be impossible, casting a doubt on whether absolute security against all the risks is achievable within the quantum context. For this reason, present attempts in this direction tend to introduce 'computational assumptions', whereby the quantum power of the eavesdropper is restricted in some appropriate way, so that interesting cryptographic primitives become possible again.

Another research trend is to consider protocols that involve many users, rather than only two: an example is the so-called 'byzantine agreement problem', which has no classical solution, but was recently shown to have a quantum one [32]. Combining many-user protocols, entanglement (see below), and possibly computational assumptions, leads to generalized forms of QKD, usually known as *quantum secret sharing*, that are presently very actively investigated.

5.5. New developpements and spinoffs related to QKD

On the research side, very significant progress has been made recently for producing single photons 'on demand'. Most of the practical realizations of QKD rely on *weak coherent pulses* (WCP) whose Poisson photon statistics imply that they must be considered only as approximations of true single photon pulses. The presence of WCPs containing two photons (or more) is an open door to information leakage towards an eavesdropper. In the presence of strong inline losses, the WCP schemes require a stronger attenuation of the initial pulse to remain secure, resulting in penalizingly low transmission rates [33,34]. The use of an efficient source of true single photons would therefore considerably improve the performance of QKD systems, especially in high-loss situations, such as satellite QKD [35]. In order to solve this problem, single photon sources have been extensively studied in recent years and a great variety of approaches has been proposed and implemented. Very recently, a complete quantum key distribution scheme based on a pulsed source of single photons on demand has been demonstrated [36]. Other schemes based on parametrically generated photons pairs have also be developed [37].

Extensive research has also been devoted to the possibility of using quadrature measurements for QKD purposes, instead of photon counting, by using non-classical light beams, such as squeezed or entangled light, rather than single-photon superpositions. Indeed, replacing single photon detection by homodyne detection has some specific advantages. Moreover, an important simplification has resulted recently when it was shown that an equivalent level of security may be obtained by transmitting coherent states, which are simply laser pulses containing a few hundred photons [38]. These new ideas, in which quantum information processing relies on the use of *continuous variables*, such as the intensity fluctuations of a macroscopic beam, rather than discrete single-photon states, open interesting perspectives towards very high bit rate QKD.

Research on quantum key distribution has also stimulated interesting technological developments (spinoffs), in particular in the field of single photon detectors. Silicon photon-counting avalanche photodiodes (APD) are very efficient in the visible and near-infrared range, and have found uses in many fields, for instance in single-molecule detection for biological applications. In the telecom range (1550 nm), QKD applications have stimulated the development of InGaAs APDs [39], and although their performance does not match yet that of silicon APDs, complete photon-counting devices have already become commercially available [31].

At the same time, QKD has stimulated technological progress in a large number of the areas, including telecom technology (development of special modulators, fibers, Faraday mirrors, ...), non-linear optics (e.g., high-efficiency parametric fluorescence in periodically poled waveguides), and software (such as, the full-size quantum cryptography software 'QUCRYPT' publicly available [40]). New developments are also expected in the direction of free-space QKD, in particular for satellite key distribution [35].

5.6. *Towards practical uses of quantum entanglement*

Many protocols going beyond QKD are based upon the use of *entanglement*, a property of quantum systems that consist of several subsystems whereby the states of the overall system are expressed as particular superpositions of the states of the subsystems (e.g., Fig. 4). Thus, through entanglement multipartite quantum systems carry physical properties that are attached to the system as a whole. A basic feature of entanglement is that it cannot be created by local operations acting only on each subpart of a system, and therefore the basic way to produce entanglement between spatially separated objects is to have them interacting at some time, and then move away. Once entanglement is created, it can be transferred to other objects, among distant nodes in a quantum network [41]. By exploiting entanglement, *quantum teleportation* has been achieved [42], that is, the re-creation of a quantum state at a distance. The re-creation process constitutes a conceptual challenge since quantum mechanics does not permit an exact measurement of all the observables of the original state so that it can be reproduced exactly. By a relying on an entangled system, however, it is possible to measure only some properties of the original state and then re-create it at a distance by using both a quantum channel, for carrying the entanglement and a classical channel for transmitting the information of the local measurement. These possibilities naturally lead to the idea of considering *shared entanglement* as a resource, that can be used to perform various tasks related to the transmission and manipulation of qubits. Such techniques are usually known under the name of *quantum communications*, and have been extensively studied from a theoretical point of view [43]. Their practical implementation, however, is presently hampered by the lack of efficient quantum memories – that is, devices that would be able to store this shared entanglement for a long time, until it is actually needed.

Advancing a little bit further into a futuristic perspective, we can point out that the availability of efficient *quantum memories* [44], and of a few elementary *quantum logic gates* [45–47], would immediately allow a new range of purely quantum communication techniques to be developed [41,43]. For instance, quantum key distribution might be achieved not by actually sending quantum objects (such as single photons), but rather by teleporting the quantum states of interest [48]. At the same time, the quality of stored entanglement could be improved, by using techniques known as *purification* and *distillation* [49]. Entanglement distributed over more than two partners would also open very intriguing possibilities for multipartite quantum information sharing [32].

The basic concepts of quantum communication relying on the exploitation of entanglement are presently in an exploratory stage, with many directions being investigated theoretically, while experiments are still lagging behind. Nevertheless, the slow but steady progress being made on the experimental side, will permit sorting all these ideas and focusing on those that can actually be implemented.

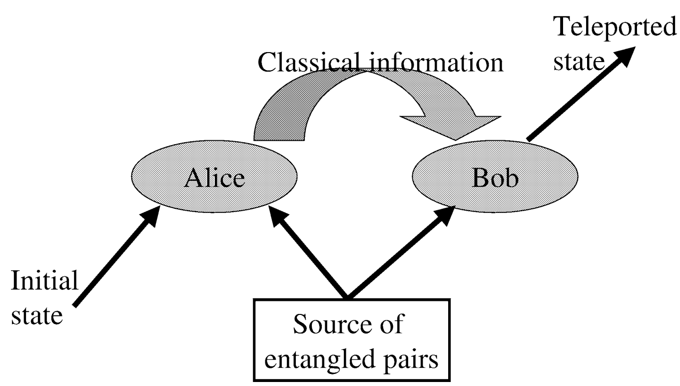

Fig. 4. Schematic presentation of quantum teleportation. Alice carries out a joint quantum measurement (a so-called Bell measurement) between the 'initial state' to be teleported, and one member of an entangled photon pair. Then she sends to Bob the result of this measurement, that consists of two bits of information for teleporting a polarized photon or a spin-1/2 particle. These two bits are related to some 'difference' between the initial state and the entangled photon, that is totally random. Therefore they say nothing about the initial state itself, that is destroyed in the Bell measurement process. Using the information received, Bob can adjust his apparatus so that the second entangled photon reproduces the initial state.

6. Conclusion

The technical progression of optical communications towards higher bit rates, longer distances, and higher sensitivity detection, has brought to the fore quantum optical phenomena in different aspects of optical communications. In this paper, we have reviewed some of the quantum aspects of optical communications, and we have discussed different solutions to transmission problems that are proposed by the development of quantum optics, as well as spinoffs that quantum optics research has generated. The pertinence of quantum optics in optical communications ranges from circumventing quantum noise that degrades the fidelity of transmission and thus constitutes a ‘nuisance’, to exploiting quantum superposition and entanglement for implementing novel functionalities that cannot be carried out ‘classically’, thus making a valuable resource out of the quantum properties of light. Although many of the proposals of quantum optics are, at present, difficult to implement in an industrial context, the impact of quantum optics on the conceptual foundations of optical communications is very important, ranging from the exploration of the ultimate physical limitations of optical communications due to quantum noise, to a re-formulation of information theory by the consideration of the quantum features of light such as superposition and entanglement. The spectacular evolution of quantum optics over the past twenty years illustrates vividly how basic research, initially motivated by the desire to understand better the quantum properties of light, now gets closer and closer to technological developments, and may soon give rise to ‘real life’ applications.

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