1 Introduction

1.1 Optics in Modern Life

The invention of the laser and the use of the special properties of laser light created one of the great technical revolutions of the twentieth century and has impact on many aspects of our modern lives. It allows us to manufacture the gadgets we love to use, including the computer with which this has been written. It allows us to communicate literally at the speed of light and with an information bandwidth that is unprecedented. Optics has been for a while the technology of choice for data storage, with DVD and Blu-ray still being used as a medium for data and 3D optical storage that might emerge in future. The modern alternatives, downloading and streaming, depend in many ways on photonics.

In addition, there is a plethora of other applications of light, from laser welding in manufacturing to laser fusion for power generation and from laser-based microscopes to laser surgery. Imaging and display technologies are in many gadgets. The developments of optical technology have been relentless and will continue to be so for many more years. This has allowed us to access new levels of power, controllability, accuracy, complexity, and low cost that were deemed impossible only a few years ago. This is a convincing reason to study and teach quantum optics, as a scientist or engineer.

Whilst all of the techniques in photonics use the quantum concept of stimulated emission and the laser [1], most of these applications still use quantum ideas in a quite simple and peripheral way. Most of the designs are based on conventional optics and can be understood on the basis of wave optics and traditional physical optics [2]. An interpretation of light as a classical wave is perfectly adequate for the understanding of effects such as diffraction, interference, or image formation. Non-linear optics, such as frequency doubling or wave mixing, is well described by classical theory. Even most of the properties of coherent laser light can be understood and modelled in this way. There is a wealth or new ideas and applications emerging, exploiting the regimes of wave optics that were previously not accessible, with new theories and devices. This includes the many fascinating new devices made possible through new engineered materials, waveguide structures, photonic bandgap materials, linear and non-linear metamaterials. They all hold the promise of even higher performance, better specifications, and even new applications, such as cloaking or 3D storage, optical data processing at unheard

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speeds, or optical data processing. Conferences and research reviews all document that in 2018 a bright future is ahead in these areas of optics.

However, which role will optics play in a future that will use quantum technologies?

Firstly, the question of what ultimately limits the performance of optical devices lies outside the classical theory of light. We have to focus on a different aspect of optics. We follow the ideas that come directly from the quantum nature of light, the full properties of photons, and the subtle effects of quantum optics [3]. Initially, optics was recognized as a pretty ideal medium to study the finer effects of the quantum world. Photons in the visible spectrum were easily generated, detected with high efficiency, and not masked by thermal noise at room temperature, and any correlations could be recorded very well.

Non-linear effects allowed the generation of a variety of different forms of light. This established optics as the medium of choice to explore the quantum world, and the early improvements in the technology in the 1980s led to great demonstrations, such as the Bell inequalities, signalling the beginning of experimental quantum optics. This exploration of the 'weirdness' of the quantum world is still today one of the frontiers in quantum optics and discussed in this guide.

It was recognized that quantum effects pose a limit to the sensitivity of many measurements, with the now successful detectors for gravitational waves the pre-eminent example. A closer analysis showed that there are ways of, at least partially, circumventing such limitations. Optical *quantum metrology* was born and is a major topic in this guide. It will continue to evolve – and we now see the first routine applications of quantum-enhanced metrology, with few photons and with laser beams. The ideas are spreading and can be realized in other systems such as coherent groups of atoms or ions or in circuits. Quantum-enhanced metrology in its various forms is becoming more widespread, from the definition of the SI units to very practical situations.

Optics technology and our knowledge of protocols and devices have steadily grown in time. Almost gone are the analogue devices of the 1990s, and we have direct access to digital data. For example, we can now detect, record, process, and store information in our experiments in much better ways, with A/D converters, multichannel analysers, memories of Terabit size, etc. This means that we can access much more information and process and analyse data more thoroughly. The next step might well include the use of artificial intelligence to optimize data analysis and also the performance of devices.

The detection of quantum correlations are a case in hand: we can now directly explore the correlation properties, use different approaches and measures to evaluate the quality of entanglement, and post-select data, or use heralded information, to select the best quantum data. This provides a path to optical quantum gates and more elaborate quantum logic. We can post-process the information and make it conditional on other measurements. This allows us to not only describe the state with tomography in great detail but also provide a path for looking inside the statistical properties of a beam of light. An example is the Wigner function shown on the front cover, which shows strong negative values that are contained in one beam from an entangled pair of beam – after conditional detection and letting information from one beam influence the reading from the other entangled beam [4].

Furthermore, so-called hybrid detection uses entangled beams, where the information from a single photon detector in one beam is used to post-select the most relevant data from stream of photon recorded from the other beam. Using this form of hybrid detection, it is possible to filter out states of light with specific quantum properties, for example, *Schrödinger cat states* [5]. They represent a state that is a quantum superposition of two orthogonal states and is one of the icons and hallmarks of quantum physics, as recognized in the 2012 Nobel Prize of Physics [6].

On the other hand, the last few years has seen an ever-increasing interest in the information that is contained within a beam of light, whether it be images, analogue pulses, or digital data encoded in the light. The emergence of the concept of *quantum information* has created a rising interest in the ability to communicate, store, and process more complex information than available in classical digital electronics, all by using beams of light or individual photons. This has created a great deal of interest, an expanding research field, and a demand for practical quantum optics-based devices. Optics overlaps more and more with condensed matter and soft matter physics, materials science, and mechanical engineering. Ever-improving technology drives these fields, as well as now insights into quantum logic and quantum control. Optics is in many cases a precursor, sometimes a testing ground, and increasingly a component of such quantum devices.

1.2 The Origin and Progress of Quantum Optics

Ever since the quantum interpretation of the black body radiation by M. Planck [7], the discovery of the photoelectric effect by W. Hallwachs [8] and P. Lennard [9] and its interpretation by A. Einstein [10] has the idea of photons been used to describe the origin of light. For the description of the generation of light, a quantum model is essential. The emission of light by atoms, and equally the absorption of light, requires the assumption that light of a certain wavelength λ, or frequency ν, is made up of discrete units of energy each with the same energy $hc/\lambda = h\nu$.

This concept is closely linked to the quantum theory of the atoms themselves. Atoms are best described as quantum systems; their properties can be derived from the wave functions of the atoms. The energy eigenstates of atoms lead directly to the spectra of light which they emit or absorb. The quantum theory of atoms and their interaction with light has been developed extensively; it led to many practical applications [11] and has played crucial role in the formulation of quantum mechanics itself. Spectroscopy relies almost completely on the quantum nature of atoms. However, in this guide we will not be concerned with the quantum theory of atoms, but concentrate on the properties of the light, its propagation, and its applications in optical measurements.

Historically, special experiments with extremely low intensities and those that are based on detecting individual photons raised new questions, for instance, the famous interference experiments by G.I. Taylor [12] where the energy flux corresponds to the transit of individual photons. He repeated Th. Young's double-slit experiment [13] with typically less than one photon in the experiment at any one time. In this case, the classical explanation of interference based on electromagnetic waves and the quantum explanation based on the interference of probability amplitudes can be made to coincide by the simple expedient of making the probability of counting a photon proportional to the intensity of the classical field. The experiment cannot distinguish between the two explanations. Similarly, the modern versions of these experiments, using the technologies of low noise current detection or, alternatively, photon counting, show the identity of the two interpretations.

The search for uniquely quantum optical effects continued through experiments concerned with intensity, rather than amplitude interferometry. The focus shifted to the measurement of fluctuations and the statistical analysis of light. Correlations between the arrival of photons were considered. It started with the famous experiment by R. Hanbury-Brown and R. Twiss [14] who studied the correlation between the fluctuations of the two photocurrents from two different detectors illuminated by the same light source. They observed with a thermal light source an enhancement in the two-time intensity correlation function for short time delays. This was a consequence of the large intensity fluctuations of the thermal light and was called photon bunching. This phenomenon can be adequately explained using a classical theory that includes a fluctuating electromagnetic field. Once laser light was available, it was found that a strong laser beam well above threshold shows no photon bunching; instead the light has a *Poissonian* counting statistics. One consequence is that laser beams cannot be perfectly quiet; they show noise in the intensity that is called *shot noise*, a name that reminds us of the arrival of many particles of light. This result can be derived from both classical and quantum models.

Next, it was shown by R.J. Glauber [15] that additional, unique predictions could be made from his quantum formulation of optical coherence. One such prediction is *photon anti-bunching*, where the initial slope of the two-time correlation function is positive. This corresponds to greater than average separations between the arrival times of photons; the photon counting statistics may be *sub-Poissonian*, and the fluctuations of the resulting photocurrent would be smaller than the shot noise. It was shown that a classical theory based on fluctuating field amplitudes would require negative probabilities in order to predict anti-bunching, and this is clearly not a classical concept but a key feature of a quantum model.

It was not until 1976, when H.J. Carmichael and D.F. Walls [16] predicted that light generated by resonance fluorescence from a two-level atom would exhibit anti-bunching, that a physically accessible system was identified that exhibits non-classical behaviour. This phenomenon was observed in experiments by H.J. Kimble et al. [17], where individual atoms were observed. This opened the era of quantum optics. It is now possible to track and directly display the evolution of the photon number inside a cavity, thanks to the innovation introduced by S. Haroche and coworkers. They have designed better and better superconducting cavities to store microwave photons and can carry out non-demolition experiments in a cavity with very long decay time. They can now directly observe the evolution of the photon number in an individual mode [18]. See for details Figure 3.7. This is a most beautiful demonstration of the theoretical concepts.

The concept of *modes* will be a central feature in this guide. This concept has evolved in time; it now has several distinct meanings and is playing a pivotal role in quantum optics. For an experimentalist, a single mode can mean a perfect beam shape without any distortion. A single-mode laser means a device that is emitting a beam with exactly one frequency, in one polarization, and with a perfect beam shape. In the theory, a *mode* is the fundamental entity that can be quantized and be described by simple operators. We have a reliable and direct model for the behaviour of such a single mode, and up to recently most quantum optics were formulated in this *single-mode model*.

At the same time, in optical technology, such as communication or imaging, the concept of a *mode* is associated with an individual channel of information. This could be a specific modulation frequency, as we are familiar with from radio transmission, or it could be a specific spatial image. In the world of optical sensing, we wish to detect and transmit changes of various parameters, such as lengths or position, magnetic or electric fields, pressure or temperature, to name a few. The evolution of these parameters are then encoded into the light and transmitted to the receiver. In this case, each parameter, and each degree of freedom for the change of the parameter, corresponds to one specific *mode*. It has now been recognized that a sensor can be optimized and will show the best possible performance, when the optical *mode* is fully matched to the information. This can be a simple mode, as mentioned in the case of the traditional *single-mode laser*, or it can actually be a much more complicated spatial and temporal distribution.

The first extension in quantum optics has been to multiple beams of light, each containing one mode each. We can have many separate beams, all originating from one complex optical apparatus. However, a single optical beam can also contain multiple modes, for example, spatial modes, temporal modes, or frequency modes. They correspond to separate degrees of freedom or separate information channels within the beam. Such a *multimode* beam might contain only a few, or the occasional, photon, or it might have the full flux of a laser beam. In either case, the underlying physics is the same. The information transmitted is best described in terms of a set of independent *orthogonal modes*. Each can be quantized individually and has their own independent statistics. The signals, and the fluctuations, transmitted by these modes do not interact with each other, and the full quantum description of these devices is straightforward using this concept.

There has been great progress in the technology to generate individual photons in a controlled way. The technology has evolved to a stage where many of the initial thought experiments dealing with individual atoms can now be performed with real machines. In addition, a whole range of new types of single photon emitters has been developed and studied by many groups around the world. They include quantum dots that show the required quantum properties and are continuously improving in their robustness and reliability. They are now being used regularly in a variety of applications where small size matters. This includes applications for quantum communication with quantum dots placed in specific places or in the form of nanodiamonds imbedded as emitters in biological samples that respond to the local conditions in living cells.

Initially, these single photon effects were a pure curiosity. They showed the difference between the quantum and the classical world and were used to test quantum mechanics. In particular, the critique by A. Einstein et al. and their EPR paradox [19] required further investigation. Through the work of J.S. Bell [20], it became possible to carry out quantitative tests. They are all based on the quantum concept of *entanglement*. In the simplest case, this means pairs of quantum systems that have a common origin and have linked properties, such that the detection of one allows the perfect prediction of the other. Such systems include not only individual photons or atoms, or coherent states of light, such as laser beams but also physical matter, such as was demonstrated with Bose–Einstein condensates. See Chapter 14.

Starting with the experiments by A. Aspect et al. [21] with atomic sources, and later with the development of sources of *twin photon pairs* and experiments by A. Zeilinger [22] and many others, the quantum predictions have been extremely well tested. The concept of *entanglement* has now been demonstrated and tested with single photons and also with intense beams of light, over large distances of many kilometres and through optical fibres. There has been a long series of experiments with the aim to demonstrate the validity and necessity of quantum physics beyond any doubt, closing step by step every loophole. It has even been possible to extend the concept of entanglement from two entities, such as two particles, to many particles, most prominently to many trapped ions. Such *multipartite entanglement* is at the core of plans to build quantum simulators and quantum logic devices. Similarly there has been an extension from two modes of light to several modes. This leads to the idea of *multimode entanglement*, which is a new topic of research, with both interesting physics and the potential for new applications.

In summary, the progress in quantum optics, which initially was concerned with the quality of the quantum demonstrations, has recently led to the conquering of complexity and the study of the robustness, or decoherence, of such complex systems. The peculiarities of single photon quantum processes have led to many new technical applications, mainly in the area of communication. For example, it was found that information sent by single photons can be made secure against listening in; the unique quantum properties do not allow the copying of the information. Any eavesdropping will introduce noise and can therefore be detected. Quantum cryptography and quantum key distribution (QKD) [23] are now viable technologies, based on the inability to clone single photons or quantum modes.

There is great anticipation of other future technological applications of photons. The superposition of different states of photons can be used to send more complex information, allowing the transfer not only of classical bits of information, such as 0 and 1, but also of *qubits* based on the superposition of states 0 and 1. The coherent evolution of several such quantum systems could lead to the development of quantum logic connections, quantum gates, and eventually whole quantum computers that promise to solve certain classes of mathematical problems much more efficiently and rapidly [24]. Just as astounding is the concept of *teleportation* [25], the disembodied communication of the complete quantum information from one place to another. This has already been tested in experiments (see Chapter 13).

Optics is now a testing ground for future quantum information technologies and for data communication and processing. At the same time, the concepts and ideas of quantum optics are emerging in other related quantum technologies, for example, based on quantum circuits or mechanical systems, which are all quantized and show in principle the same physics. We can see the equivalence of the physics of photons, phonons, polaritons, and other particles that describe the excitation of quantum systems. Technology is moving very fast, and we can expect over the next decade to see machines that utilize any of these individual quantum systems or even combine several of them. The rules of quantum optics, as described in this guide, will become important in many different other types of instruments. Optics could become one of the best ways to visualize the broader quantum concepts that apply to many other types of instruments.

1.3 Motivation Through Simple and Direct Teaching Experiments

The best starting point for the demonstration of photons in current technology is to start with images that are generated by CCD (charge-coupled device) cameras. It is worthwhile to note that basically all information we have about light and optical effects is based on either some form of photodetector or the human eye. The first generates an electric signal, either pulses or a continuous photon current. Whilst the eye produces, in a clever and complex way, a signal in the neurones in the brain, even they can be interpreted as a form of electric signal. It is the characteristics of these signals and their statistics that provides access to the quantum properties of light.

In the extreme case we would have a detector that is capable of detecting one individual photon at a time. This is now possible with special CCD cameras, where the sensitivity has been lifted to such a high level and thermal noise has been reduced so much that it hardly interferes with the observation. The number of dark counts, that is, clicks that are generated at random without photons present, can be neglected. In this way we can actually detect and record images at the single photon level as shown in Figure 1.1.

The human eye is actually capable of seeing at this level, and many animals exceed our capability. At this level of illumination, the world looks very grainy. We can see individual events. The image is composed out of individual local detection events. An example, taken with a special CCD, is shown in Figure 1.1. At some level this can be regarded as trivial – obviously it will be like this. We have photons. On the other this image demonstrates several subtle points. We can see that the concept of intensity, bright and dark, is directly related to the concept of probability. Areas with a high local photon flux, or high probability, correspond to high intensities, that is, a high amplitude of the electromagnetic field. Conversely, dark areas of the image correspond to a low intensity. The central concept in quantum science of a probability amplitude become directly obvious.

Two, or many, waves with different amplitudes and relative phases can interfere, and this is a central concept of the classical wave picture of light. The example

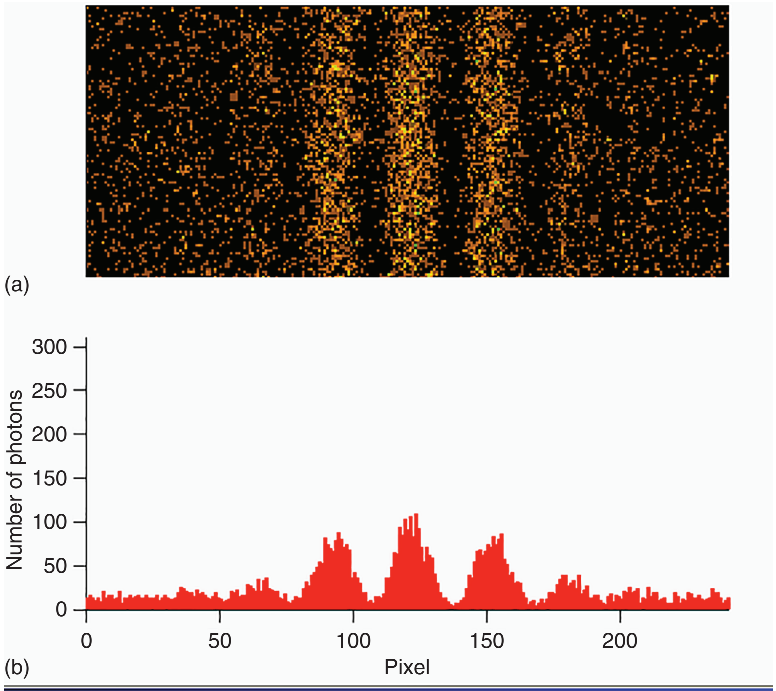

Figure 1.1 Image of the fringes from a double-slit experiment recorded at the single photon level. (a) Distribution of individual photons. (b) Histogram of photons in each vertical line. The full movie can be seen at https://www.lcf.institutoptique.fr/Groupes-de-recherche/Gaz-quantiques/Membres/Permanents/Alain-Aspect. Source: After https://www.lcf.institutoptique.fr/Groupes-de-recherche/Gaz-quantiques/Membres/Permanents/Alain-Aspect.

shown in Figure 1.1 is a real interference fringe system, generated with coherent light and a double-slit apparatus. This is one of the simplest arrangements that shows the wave nature of light – and yet in this case it is detected by a number of individual photons. There is no contradiction here – the two explanations, waves and particles, are fully complementary. The shape of the fringes, the overall intensity function, is best described with the wave model. At the same time, the statistics of the light, the visibility that is observed, and thus the quality of the fringes can best be described with the photon model. This very simple example immediately shows the strengths and weaknesses of both models. It demonstrates how we want to use these two models for different aspects of the experiment. We should choose the pictures in our mind that is most suitable to understand the specific aspect of the experiment we wish to investigate.

The next level would be to quantify the statistics. What would be an appropriate statistical model for the fluctuations, detected in one specific area of the image and averaged over many time intervals? Equivalently we could ask: what is the statistics of the number of photons detected in many separate areas of equal size, all receiving the same intensity? In the first case one could imagine listening to the number of *clicks* being generated. It would sound like a random sequence of *clicks*, as we know them from a Geiger counter detecting α or γ rays.

A proper analysis would reveal that we have a Poissonian distribution for the different time intervals. The same result applies to the analysis of the number of photons in many image areas of equal size. The graininess we see in Figure 1.1 is a direct representation of the counting statistics, which can be derived from simple statistical arguments, assuming random processes.

The randomness in the arrival times of the photons in a weak beam of light is so perfect that it is now used as the gold standard for randomness, exceeding in quality the widely used random number generators based on electronic processes or imbedded in computers. This has led to commercial activities where optically generated random numbers now can be accessed via the internet and the generators are for profit. The demand is substantial – and already a small niche market for quantum random numbers has emerged.

The 1960s saw a rapid development of new laser light sources and improvements in light detection techniques. This allowed the distinction between incoherent (thermal) and coherent (laser) light on the basis of photon statistics. The groups of F.T. Arecchi [26], L. Mandel, and R.E. Pike all demonstrated in their experiments that the photon counting statistic goes from super-Poissonian at the lasing threshold to Poissonian far above threshold. The corresponding theoretical work by R.J. Glauber [15] was based on the concept that both the atomic variables and the light are quantized and showed that light can be described by a *coherent state*, the closest quantum counterpart to a classical field. The results are essentially equivalent to a quantum treatment of a classical oscillator. However, it is an important consequence of the quantum model that any measurement of the properties of this state, intensity, amplitude, or phase of the light, will be limited by these fluctuations. This is the optical manifestation of Heisenberg's uncertainty principle.

Quantum noise can impose a limit to the performance of lasers, sensors, and communication systems, and near the quantum limit the performance can be quite different. To illustrate this, consider the result of a very simple and practical experiment: use a laser, such as a laser pointer with a few milliwatt of power, and detect all of the light with a photodiode. The average number of detection events is now very large. Listening to the output, we can no longer distinguish between the individual clicks; we will hear a continuous *noise*. The level of noise will increase with the intensity, as the width of the Poissonian distribution increases with the average number of photons detected. This *quantum noise* is the direct experimental evidence of the quantum statistics of light. If we record the current from the photodetector on an oscilloscope, we would see a trace with random fluctuations, above and below a mean level, representing the average intensity. The excursions have a Gaussian distribution around the mean value, which is fully consistent with the transition from a Poissonian to a Gaussian distribution. Relatively speaking this effect gets smaller if we average the signal over more photons, that means using a brighter laser or measuring for a longer time. As we will see, this effect cannot be avoided completely. Quantum noise is not an effect that can be eliminated by good traditional engineering. Decades ago quantum noise was called *shot noise* and was regarded by many as a consequence of the photodetection process, as a randomness of the stream of electrons produced in the photodetector. This view prevailed for a long time,

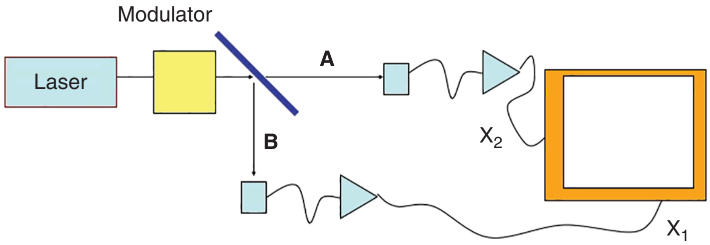

Figure 1.2 Experiment to investigate the correlation between two parts of a laser beam, using a laser pointer, modulator, two detectors, and an *x*–*y* oscilloscope.

particularly in engineering textbooks. However, this view is misleading as we find in the *squeezing* experiments described in this book. It cannot account for situations where non-linear optical processes modify the quantum noise, whilst the detector remains unchanged. In the squeezing experiments the quantum noise is changed optically, and consequently we have to assume it is a property of the light, not of the detector.

Today it is straightforward to see these effects of quantum noise with simple equipment, accessible to undergraduate students. The light source can be a laser pointer, carefully selected to operate in a single mode. The laser beam is split by a beamsplitter into two beams of equal power that are detected by two individual detectors, A and B, at different locations. Each photocurrent is amplified, and they are both displayed via the x and y axes of one oscilloscope. We want to see both the average (DC) value of the photocurrent, which represents the time averaged intensity of the beams A and B, and the fluctuations (AC) of the two photocurrents, as they represent any modulation and the fluctuations, or noise, of the intensity of the two beams. This can easily be done by looking at the signals at a few megahertz, which is typically the bandwidth of the RF amplifiers used. This is shown in Figure 1.2.

The laser can be modulated, through periodic variations of the laser current. Classical optics predicts that the intensity of both beams A and B will be modulated, and this will show up clearly as a line at 45° on the oscilloscope. That means the two photocurrents change synchronously in time, an increase in one is accompanied by an increase in the other etc. In practice some care is required to achieve a clear 45° line: there should be no delay in the signals from the detector to the oscilloscope and the size of the signals has been matched. This result shows a strong *correlation* between the two beams. A correlation of the photocurrents means a correlation of the flux of photons.

We can also look at the fluctuations in more detail. If we look at beams A and B individually, we see fluctuations of the current above and below the long-term average value. Closer inspection would show a Gaussian distribution of the excursions below and above, as we expect it for random noise in the beam. The magnitude of the fluctuations will follow the gain curve of the RF amplifiers. With careful calibration of the frequency response of our equipment, we find that the noise in the light is not frequency dependent; it is *white noise*. The magnitude of the fluctuations is the same for a laser beam with or without a small modulation.

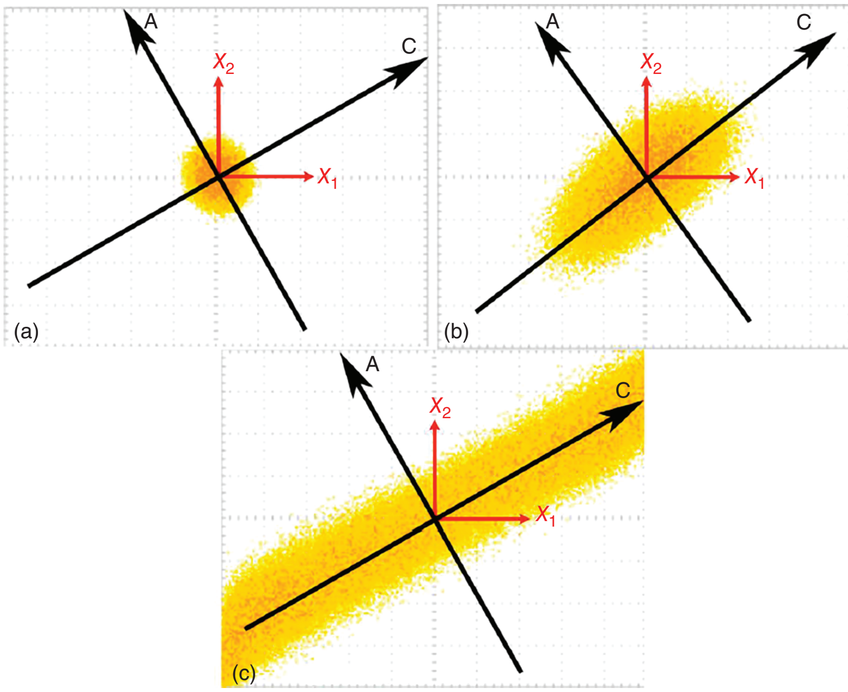

Figure 1.3 The noise of beams A and B displayed on an oscilloscope. (a) No beam, technical background noise. (b) The laser beam has no modulation, quantum noise. (c) The laser beam with modulation. The signal from the two detectors is displayed in the coordinates X_1 and X_2, correlations appear in the direction C, and uncorrelated signal appears in both directions A and C.

The noise increases with intensity, and careful measurements show that the variance of the noise is proportional to the intensity.

Is the noise from A correlated with the noise from B? The oscilloscope image immediately provides the answer. The noise from A and B results in a fuzzy blob on the screen. See Figure 1.3b. The fluctuations in the two photocurrents are independent. The point on the screen of the oscilloscope traces out a random walk independently in both directions. This is in stark contrast to the modulation where the photocurrent fluctuates synchronously, as shown in Figure 1.3c. The lack of correlation is immediately evident. This confirms the special properties of quantum noise; it does not obey the classical rules.

One simple explanation is that for small fluctuations we would notice the effect that one photon cannot be split into halves at the beamsplitter. It will appear in one or the other beam, with a random choice which beam it will join. We will see in Chapter 3 how this simple statement leads to an explanation of the properties of quantum noise in this situation. If we have no modulation, the blob is right in the middle of the screen. The blob is circular, given there is no additional noise in the system and the photon noise dominates over the electronic noise generated in the apparatus. For a laser beam with modulation, we will see a fuzzy area tilted at 45°, as shown in Figure 1.3c. This is a combination of the two effects, a line in direction C for the modulation and a fuzzy blob for the laser noise. Classical modulations and quantum noise have different properties, even when they have similar magnitudes, and this simple experiment can show the difference.

1.4 Consequences of Photon Correlations

It is worthwhile to explore the properties of quantum noise somewhat further. It was found that, in clear distinction to classical noise, no technical trick can eliminate quantum noise. This becomes evident from our experiment. A common conventional idea for noise suppression would be to make two copies of the signal, both containing the noise, and to subtract them for each other. We have all the necessary components in the apparatus used in Figure 1.2. We have made two copies of the beam. We can use one beam, say, A, for our experiment, record it with detector A, and then subtract the electronic fluctuations generated by detector B. Based on our observations we now see that we can subtract the classical modulation, which is common to both beams. However, we cannot subtract the quantum noise, which is independent and uncorrelated.

The subtraction works for any modulation, for harmonic modulation demonstrated here, and for random intensity modulations, such as those generated by a low-quality, noisy current source for the laser. That means we can distinguish between classical laser noise and quantum noise that is a consequence of the quantum properties of the photons. The result remains unchanged if the subtraction is replaced by a sum or if the two currents, or if the two currents are added with an arbitrary short time delay, such as introduced be an extra length of cable. The resulting noise is always the quadrature sum of the two-input signal. It is independent of the sign, or phase, of the summation. This is equivalent to the statement that the noise in the two photocurrents is not correlated.

At this stage it is not easy to identify the point in the experiment where this uncorrelated noise is generated. One interpretation assumes that the noise in the photocurrents is generated in the photodetectors. A different interpretation assumes that the beamsplitter is a random selector for photons and consequently the intensities of the two beams are random and thus uncorrelated. A distinction can only be made by further experiments with squeezed light, which are discussed later in this book.

An alternative scheme for noise suppression is the use of feedback control, as shown in Figure 1.4. It achieves equivalent results to difference detection. The

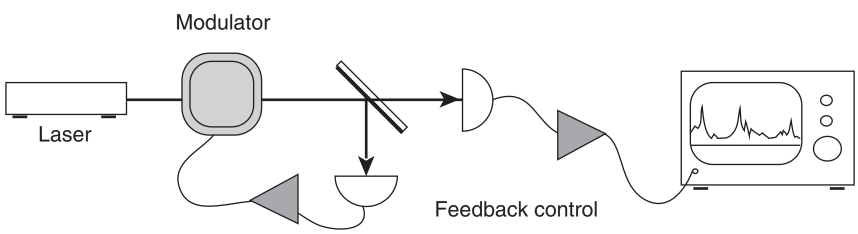

Figure 1.4 The second attempt to eliminate laser noise: an improved apparatus using a feedback controller, or 'noise eater'.

intensity of the light can be controlled with a modulator, such as an acousto-optic modulator or an electro-optic modulator. Using a feedback amplifier with appropriately chosen gain and phase lag, the intensity noise can be reduced, and all the technical noise can be eliminated [27]. It is possible to get very close to the quantum noise limit, but the quantum noise itself cannot be suppressed [28, 29]. This phenomenon can be understood by considering the properties of photons. As mentioned above, the quantum noise measured by the two detectors is not correlated; thus the feedback control, when operating only on quantum noise on one detector, will not be able to control the noise in the beam that reaches the other detector. This can be explained using a full quantum theory.

The role of the photon generation process can be explored further. It was found that the noise of the light may be below the standard quantum limit if the pumping process exhibits *sub-Poissonian* statistics. This is particularly easy to achieve for LEDs, which are high efficiency light sources driven directly by electric currents, or with semiconductor lasers. The currents driving these devices are classical, at the level of the fluctuations we are concerned with, and the fluctuations can be controlled with ease to levels well below the shot noise level. For sources with high quantum efficiencies, the sub-Poissonian statistics of the drive current is transferred directly to the statistics of the light emitted. Such experiments were pioneered for the case of diode lasers by the group of Y. Yamamoto [30]. They showed that intensity fluctuations can be suppressed in a high impedance semiconductor laser driven by a constant current. Similar work had earlier been carried out with LEDs by several groups. If we use this type of source in our experiment shown in Figure 1.3, the fuzzy blob would be smaller, in both directions, than the blob for a normal laser with the same output intensity.

To explain the quantum noise and the correlations fully, we should not restrict ourselves to fluctuations of the intensity of the light or the statistics of the photon arrival time. We will find that there is noise both in the magnitude and phase of the electromagnetic wave. Consequently our quantum model requires a two-dimensional description of the light, with properties which we will call *quadratures*. Fluctuations, or noise, can be characterized by the variance in both the amplitude and phase quadrature.

Almost a decade after the observation of photon anti-bunching in atomic fluorescence, another quantum phenomenon of light was observed – the suppression, or squeezing, of quantum fluctuations [31]. For a coherent state the uncertainties in the quadratures are equal and minimize the product in Heisenberg's uncertainty principle. A consequence is that measurements of both the amplitude or the phase quadrature of the light show quantum noise. In a *squeezed state*, the fluctuations in the quadratures are no longer identical. One quadrature may have reduced quantum fluctuations at the expense of increased fluctuations in the other quadrature. Such squeezed light could be used to beat the standard quantum limit. After the initial theoretical predictions, the race was on to find such a process. A number of non-linear processes were tried simultaneously by several competing groups. The observation of a squeezed state of light was achieved in 1985 first by the group of R.E. Slusher at Bell Labs in four-wave mixing in sodium atomic beam [32], soon followed by the group of M.D. Levenson and R. Shelby at IBM [33] the group of H.J. Kimble with an optical parametric oscillator [34]. In recent years a number of other non-linear processes have been used to

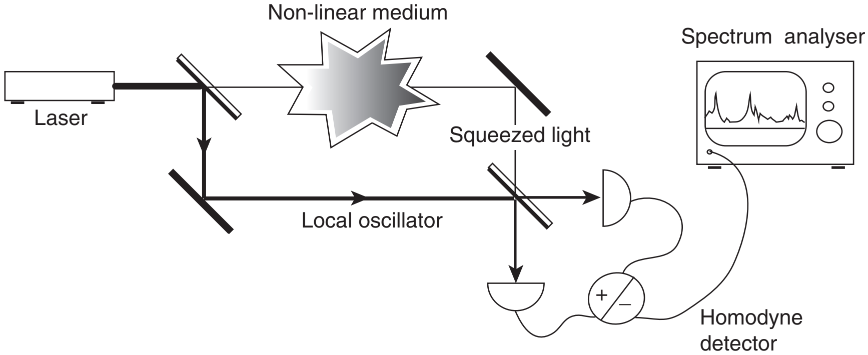

Figure 1.5 A typical squeezing experiment. The non-linear medium generates the squeezed light that is detected by a homodyne detection scheme.

demonstrate the quantum noise suppression based on squeezing [35]. A generic layout is shown in Figure 1.5. The experiments are now reliable, and practical applications are feasible.

Quantum information is a key to many applications of quantum optics. Plans for using the complexity of quantum states to code information, to teleport it, to use it for secure communication and cryptography, and to store quantum information and possibly use it for complex logical processes and quantum computing have all been widely discussed and demonstrated to a greater or lesser degree. The concept of *entanglement* has emerged as one of the key qualities of quantum optics. As it will be shown in this guide, it is now possible to create entangled beams of light either from pairs of individual photons, which is now possible in technical applications and in teaching laboratories [37], or from the combination of two squeezed beams, and the demand and interest in non-classical states of light has sharply risen. We can see quantum optics playing a large role in future communication and computing technologies [23, 36]. For this reason, the guide covers both single photon and CW beam experiments parallel to each other. It provides a unified description and compares the achievements and tries to predict the future potential of these experiments.

1.5 How to Use This Guide

This guide leads us through experiments in quantum optics, experiments that deal with light and demonstrate, or use, the quantum nature of light. It shows the practicalities and challenges of these experiments and gives an interpretation of their results. One of the current difficulties in understanding the field of quantum optics is the diversity of the models used. On the one hand, the theory and most of the publications in quantum optics are based on a rigorous quantum model that is rather abstract. On the other hand, the teaching of physical optics and the experimental training in using devices such as modulators, detectors, and data acquisition systems are based on classical wave ideas. This training is extremely

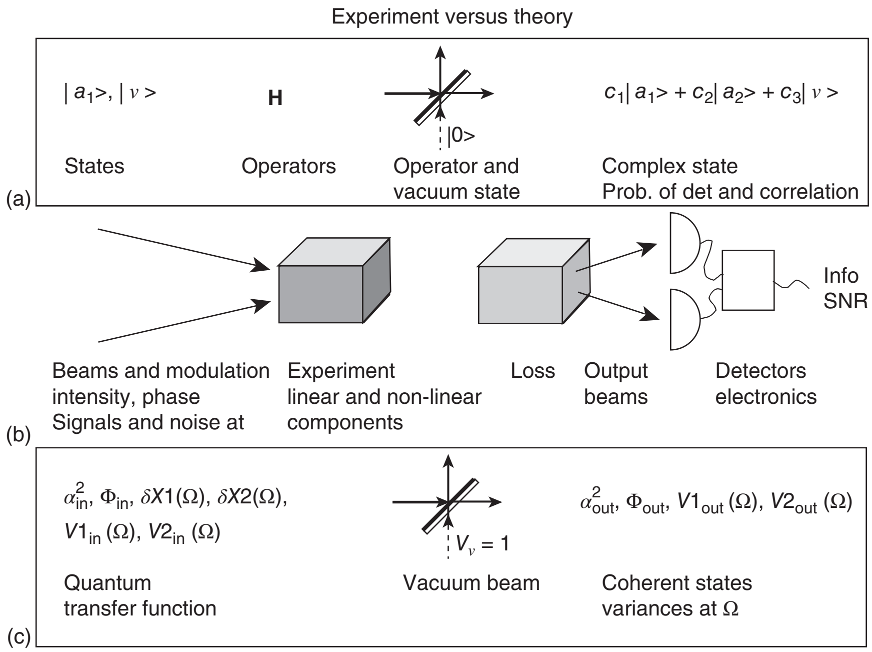

Figure 1.6 Comparison between an experiment (b) and the two theory descriptions for few photon states (a) and laser beams (c).

useful, but frequently does not include the quantum processes. Actually, the language used by these two approaches can be very different, and it is not always obvious how to relate a result from a theoretical model to a technical device and vice versa. As an example compare the schematic representation of a squeezing experiment, shown in Figure 1.6, both in terms of the theoretical treatments for photons and laser beams and in an experimental description. The purpose of this guide is to bridge the gap between theory and experiment. This is done by describing the different building blocks in separate chapters and combining them into complete experiments as described in recent literature.

This guide starts with a classical model of light in Chapter 2. Experiments reveal that we require a concept of photons, Chapter 3, which is expanded into a quantum model of light in Chapter 4. The properties of optical components and devices are given in Chapter 5, followed by a detailed description of lasers and amplifiers in Chapter 6. Next is a detailed discussion of photodetection for single photons and beams in Chapter 7. On this basis we build with the discussion of complete experiments. The technical details required for reliable experimentation with quantum noise, including techniques such as cavity locking and feedback controller, are given in Chapter 8. The concept of squeezing is central to most attempts to improve optical devices beyond the quantum noise limit and is introduced and discussed in Chapter 9. It also describes the various squeezing experiments and their results are discussed; the different interpretations are compared. Finally, the applications of squeezed light are described in Chapter 10 with a detailed description of the largest application, the detection of gravitational waves. Similar to squeezing Chapter 11 discusses quantum non-demolition experiments. In Chapter 12 more and more complete experiments to test the fundamental concepts of quantum mechanics are discussed. Finally, the concepts of quantum information and the rapidly evolving state of art in using quantum optics, both single photons or CW beams, in quantum information devices are presented in Chapter 13. Quantum optics has helped to build the foundations of many other form of quantum technology, and the links to these many parallel lines of research is briefly outlined in Chapter 14, which tries to look a little into the future.

This guide can be used in different ways. A reader who is primarily interested in learning about the ideas and concepts of quantum optics would best concentrate on Chapters 2–4, 9, 12, and 13 but may leave out many of the technical details. For these readers Chapter 5 would provide a useful exercise in applying the concepts introduced in Chapter 4. In contrast, a reader who wishes to find out the limitations of optical engineering or wants to learn about the intricacies of experimentation would concentrate more on Chapters 2, 5, 6, and 8, and for an extension into experiments involving squeezed light, Chapters 9 and 10 can be added. A quick overview of the possibilities opened by quantum optics can be gained by reading Chapters 3, 4, 6, 9, 11–14.

We hope that in this way our book provides a useful guide to the fascinating world of quantum optics.

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