Photonics, at the single-photon level

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Inaugural lecture
prof.dr. Andrea Fiore
15 May 2009

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Where innovation starts
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Photonics, at the single-photon level

Presented on 15 May 2009
at the Eindhoven University of Technology
Light, or more precisely electromagnetic radiation at optical frequencies, obviously plays a key role in life on our planet: it keeps the surface warm, provides energy for atmospheric processes and biochemical reactions, and represents the most powerful means of sensing our environment. Interestingly, however, the physical nature of light has remained unclear and was the subject of controversy for many centuries, until the wave and corpuscular descriptions were re-unified in the context of quantum mechanics in the first decades of the 20th century. Only after the work of Einstein, Planck and Dirac did it become clear that the energy in the electromagnetic field is quantized, i.e. it comes in multiples of an elementary excitation. As interactions between light and matter involve the exchange of this energy quantum, they can conveniently be described as collisions with ‘light particles’ (photons). The energy quantum (energy of a photon) is extremely small ($\approx 3\times10^{-19}$ J in the visible) compared with macroscopic energy scales, so that we do not experience the effect of quantization in everyday life.

Because of the late development of a consistent understanding of light, its application has long remained very limited, apart from its basic use for lighting. Only after the invention of the laser in 1958, when a source of powerful, coherent and short light pulses became available, did the science of light blossom into one of the pillars of today’s information society. As the term suggests, ‘photonics’ is a field of science and technology which aims at using photons to perform functions which have traditionally been reserved for electronics, in particular in communication, information storage and sensing. Indeed, the first widespread application of photonics was in long-distance optical communications, which exploit the fact that photons can propagate for very long distances due to their chargeless nature and resulting weak interaction with the environment. Nowadays, applications such as displays, information storage, lighting, solar energy, medical technology and defense have an even greater economic and social impact than that of optical communications. The photonics sector employs over 250,000 people in Europe alone, and is expected to maintain a strong growth rate in the coming decade$^1$.

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One of the drivers for the success of electronics has been the continuous downscaling of device size and the increase of the integration level, commonly known as Moore’s law\textsuperscript{2}: progress in microfabrication technology allows reduction of transistor dimensions, which in turn leads to smaller capacitance and higher speed. Also the number of electrons coding a logical bit scales with the device area, and has decreased by over three orders of magnitude in the last 30 years (it is now in the range of $10^4$ electrons/bit). A similar trend towards smaller and faster devices operating on a smaller number of photons is observed in photonics. The laser cavity length has decreased from $\approx 1$ m in the first gas and solid-state lasers, to $< 1$ mm in semiconductor diode lasers, and more recently to $< 1$ µm in microcavity lasers. Thousands (and in principle millions) of lasers can now be produced on a single chip, lowering production costs and allowing widespread application. The energy (number of photons) in an optical pulse produced by these smaller devices is also smaller. An optical communication system can presently operate at a level of 1000 (received) photons per bit. This number can further be reduced to the level of a few tens of photons by improving the detectors, and to the level of one or a few photons by using non-classical light (see the following sections). Reducing the energy per bit is particularly important in both electronic and photonic integrated circuits, as it sets the ultimate limit to the total power dissipation. As well as in communications, energy scales corresponding to one or a few photons are also reached in sensing applications. The need to increase sensitivity leads us to the single-photon limit in application fields such as biomedical imaging, testing of integrated circuits, 3D imaging and astronomy. As an example, the optical signals collected from faint astronomical objects correspond to a few photons per second.

\textsuperscript{2} G.E. Moore, Electronics, 38, (8), 1965
As we approach the quantum limit of one elementary excitation (a single photon) in the electromagnetic field, the particle-wave duality produces interesting and counterintuitive effects. On the one hand we can generate and detect photons one by one, indicating their discrete nature, so that we would be tempted to treat them as classical particles. But on the other hand they retain their wave properties, so that for example a single photon can show interference patterns in an interferometer (Fig. 1). To reconcile the particle and wave pictures, we should note that a single photon, like any quantum-mechanical object, can exist in a superposition of states. When it enters the interferometer, it propagates in a coherent superposition of the two states ‘photon in lower arm’ and ‘photon in upper arm’. In the language of quantum information processing, the photon is a quantum bit (qubit) in a superposition of bits ‘0’ (lower arm) and ‘1’ (upper arm), and the corresponding amplitudes interfere on the second beam splitter. This simple optical system then becomes an illustration of the superposition principle of quantum mechanics. Even more dramatic and counterintuitive results are found when looking at multi-photon effects, e.g. interference between two photons and entanglement. Because photons can relatively easily be generated and detected, single- and few-photon physics has been the ideal playground for testing the

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3 The term ‘coherent’ here refers to the fact that interference effects can be expected. In contrast, if a photon is sent either to one arm or to the other (for example by using a rotating mirror instead of the beam splitter), fringes will not be observed.
predictions of quantum mechanics and improving our understanding of quantum physics. Since photons interact only weakly with the environment, qubits coded into position or other physical properties of the photon (phase, polarization...) can be transmitted over long distances (up to tens of km), allowing the exchange of quantum information between distant parties. One of the applications of photonic qubits is the distribution of cryptographic keys (secret sequences of random bits) to be used for secure communications – I will come back to this novel application field known as ‘quantum key distribution’ at the end of this lecture. Qubits can also be used to perform certain computational tasks in a more efficient manner, and quantum computers may in the future help to solve problems which are presently intractable.

In the following, I will describe some of the key issues and approaches in the problem of generating, manipulating and detecting light at the single-photon level, in other words the research and application field that we may broadly define as ‘single photonics’.
Sources of single photons

With the (somewhat vague) term ‘single photon’ we refer to a state of the electromagnetic field where exactly one excitation is present in a given spatio-temporal mode. This is a highly non-classical state with no fluctuations – the equivalent of an electrical current without shot noise. It is important to note that an attenuated laser beam, or the emission from a thermal source, does not produce single-photon states. Indeed, even when the average photon number is reduced to $\approx 1$, these sources present an inherent spread in the photon number distribution, so that zero, one, two or more photons can be measured. This is a direct consequence of the large number of atoms contributing to the emission. In contrast, when the radiation of an individual emitter (atom or molecule) is isolated, a stream of single-photon pulses is obtained\(^4\) (see left part of Fig. 2). Indeed, an atom pumped to the upper level of a radiative transition relaxes to the ground state by emitting a single photon – it has to be re-excited to emit another photon. In practice however it is difficult to isolate and efficiently collect light from a single atom. Additionally, solid-state systems are clearly required for any practical application. Single semiconductor nanostructures (‘quantum dots’, QDs) are promising candidates for such applications. QDs are nanosized islands of low-bandgap semiconductor in a higher-bandgap matrix (e.g. InAs in GaAs, see right part of Fig. 2). They can conveniently be fabricated with conventional

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\(^4\) The presence of zero-photon events can never be avoided, since any optical system has loss. The key goal here is to avoid multiple-photon events, which may undermine the security of a quantum key distribution system or produce errors in optical quantum computers.
semiconductor epitaxy systems using self-organization methods. The electrons are confined in the nanoscale low-bandgap island (typical dimensions 10-20 nm), which results in a discrete energy spectrum and strong carrier correlation effects, making the energy of each electronic configuration (excitons, biexcitons, multiexcitons) easily distinguishable. While each QD can in practice contain several excitons, and will thus emit several photons after the excitation, by spectrally isolating the photon emitted by the last exciton a single-photon pulse is obtained. Single-photon emission from self-assembled QDs was demonstrated almost 10 years ago [1], and QD-based single-photon sources have been intensively investigated in the last few years. My group, previously at the Ecole Polytechnique Fédérale de Lausanne and now at TU/e, has in particular contributed to the development of single-photon sources emitting at telecommunication wavelengths [2] (for transmission in optical fibers), and of nanostructured devices for electrically-driven single-photon sources [3].

As the mechanism of single-photon emission in semiconductors is now relatively well understood, and optimized devices (in terms of efficiency, purity, speed, wavelength...) are becoming available, the research emphasis is shifting towards the fabrication and investigation of integrated arrays of sources of identical single photons. Identical refers here to the emission spectrum and timing: all emitters should have the same, transform-limited spectrum, and the emission time should be controlled so that any two photons can be made to arrive simultaneously at a beam splitter. These conditions are required to obtain quantum interference effects, which lead to single-photon nonlinearities and can thus be used for photonic quantum computation. However they pose very challenging requirements to the technology, as self-organized QDs grow randomly on the surface and typically present a distribution of sizes and emission energies. Additionally, the emission time and the photon temporal waveform are difficult to control as they are determined by the spontaneous emission process, occurring at fast ($\approx$ ns) timescales. A large effort is currently being made in our group, as well as in several other labs worldwide, to gain better control over QD positioning and emission energy, and to control their temporal properties by the use of optical cavities and electric fields.
A single-photon detector is an optical detector which provides a measurable electrical pulse in response to the absorption of a single photon. Single-photon detectors are needed not only for quantum photonic applications, but in any application where the ultimate optical sensitivity is required. For example, in order to characterize the energy transfer dynamics within biological molecules, the emission lifetime of single fluorophores is measured. As the collected optical signals are very weak, the only viable approach is to record the arrival time of each detected photon, and to reconstruct the fluorescence dynamics from the histogram of arrival times. Similar techniques are used to image the switching dynamics of transistors in integrated circuits, and to produce a 3D image of an object by measuring the arrival delay of the back-scattered light under illumination with short pulses.

However, the energy of a single photon is extremely small ($\approx 10^{-19}$ J) on a macroscopic scale, which makes it very difficult to detect. A conventional detector (for example a photodiode), which typically converts each absorbed photon into an elementary charge flowing in the external circuit, when illuminated by a single photon, produces a current pulse too small to be discriminated from the noise of the read-out circuit. Interestingly, rod cells in human eyes are sensitive to single photons in the visible wavelength region, due to an internal biochemical gain process, but their response is very slow, in the 300 ms range [5]. For many applications, and particularly quantum communications, single-photon detectors are needed with sensitivity in the 1300-1550 nm fiber transmission wavelength range, and with response times in the sub-ns range – the corresponding $\approx$ GHz bandwidth makes low-noise preamplification particularly challenging. Detectors with an internal gain mechanism, such as photomultipliers (PMTs) and avalanche photodiodes (APDs), are therefore needed. For example in avalanche photodiodes, photo-generated electrons are accelerated by a strong electric field until their kinetic energy is sufficient to generate more electron-hole pairs through collisions with bound electrons. The cascade of these ‘impact ionizations’ can produce a current avalanche which is limited only by electrical feedback in the external circuit.

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5 By using cryogenic integrating preamplifiers, a single-photon sensitivity can be obtained in the visible range [4], but only with a low electrical bandwidth ($\approx$ kHz), which is insufficient for most applications.
circuit, and gives rise to a sizeable current pulse. Very sensitive and relatively fast single-photon APDs can be fabricated out of silicon, with optical response in the visible range (up to $\approx 1000 \text{ nm}$, limited by the silicon bandgap). However, in the most interesting 1300-1550 nm wavelength range, only InGaAs or Ge APDs can be used. These present much higher noise due to the lower material quality (APDs are extremely sensitive to crystal defects, since they operate at very high internal fields). The high noise ($\approx 10^4$ dark counts/sec) and low speed ($\approx \text{MHz}$) of APDs is presently the major limitation to the maximum distance and bit rate of quantum key distribution systems, so that other technologies are being investigated. Among these, detectors based on superconducting nanostructures (‘superconducting single-photon detectors’, SSPDs) have recently gained wide recognition as the most sensitive and fastest single-photon detectors. Developed only a few years ago [6], they are based on the photon-induced heating of the electron population in a superconducting nanowire (see schematics in Fig. 3): the absorption of a single photon promotes a large number of electrons from the superconducting to the normal state, creating a ‘hot spot’, i.e. a local resistive region in a narrow ($\approx 50-100 \text{ nm}$) and thin ($\approx 4-10 \text{ nm}$) stripe where a supercurrent is flowing. As the supercurrent avoids the hot spot and accumulates towards the edge of the stripe, the critical current density is reached in these regions and the entire section of the stripe becomes resistive, producing a voltage pulse in the external circuit. Here the carrier multiplication process (many normal electrons from one photon) stems from the fact that the photon energy is much larger than the superconducting gap, and is made possible by the low operating temperature ($\approx 2-4 \text{ K}$), which in the absence of a photon ‘freezes’ the electrons in the superconducting state. Sensitivities 3-4 orders of magnitude higher than in APDs, and response times 10 times faster, have been obtained, at the price of the cooling
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requirement. SSPDs have already been used to demonstrate quantum key
distribution at record distances of > 200 km [7], and to perform other single-
photon experiments [8] which are impossible with APDs.
Apart from their sensitivity, superconducting nanowires offer the possibility of
investigating novel and useful functionalities. This is related to their very simple –
although technologically challenging – structure, and the intrinsically nanoscale
character of their response (the initial photon-induced hot spot has a diameter in
the ≈ 30 nm range). Indeed our group, in collaboration with groups in Moscow and
Rome, recently demonstrated a novel detector structure capable of measuring the
number of photons in an optical pulse, in the 1-6 photon range [9]. This ‘photon-
number-resolving’ functionality, not present in standard single-photon detectors
(which only measure the presence/absence of light), is particularly important for
the development of photonic quantum gates and quantum memories. We are now
aiming at further developing this idea towards a detector which would provide a
linear response in the 1-100 photon range, bridging the gap between single-
photon detectors and conventional linear detectors. An additional and exciting
area is the study of the physics of nanoscale hot-spot formation, and the
corresponding investigation of the ultimate limits of spatial resolution in single-
photon detection – in essence, looking at quantum-optic phenomena on the
subwavelength scale.
Light-matter interaction at the single-photon level

The absorption and emission of photons by electrons in solids is the very basis for the investigation and application of light. Usually, electron-photon processes occur at macroscopic scales and in large numbers, so that their quantum character is not apparent. The first experimental evidence of this quantized nature came from the investigation of the photoelectric effect by Hertz, Thomson, Van Lenard and Millikan in the late 1800s-early 1900s\(^6\), and was interpreted by Einstein in 1905. However, the full illustration of quantum mechanics applied to electron-photon interaction came only much later (in the 1980s and 90s), with experiments on single atoms in optical or microwave cavities (for a review see [10]). In this system (see left part of Fig. 4), a single atom can be placed within a cavity, which has a resonant mode at an energy corresponding to an electronic transition of the atom. Due to highly reflective mirrors, emitted photons are trapped in the cavity for a long enough time to allow them to be reabsorbed by the atom, leading to a periodic energy exchange between the field and the atom. In other words, the atom-field system can interact in isolation from the environment, in contrast to the conventional case of spontaneous emission in free space, in which any emitted photon escapes and never sees the atom again. This system is particularly exciting for fundamental studies of quantum mechanics, as it allows us to probe the evolution of two strongly-coupled quantum-mechanical objects isolated from their environment – such simple cases are indeed rare in nature. One of the amazing consequences of this evolution is the possibility of creating a coupled (‘entangled’) state of light and matter, where the total system is in a well-defined state, but it is impossible even in principle to determine the state of its constituents. Let us consider an example. The atom in the cavity is first excited to the upper level of the transition, and then left to interact with the cavity field for just half of the time needed to emit a photon. Then either the photon or the atom is taken out of the cavity. In this situation, quantum mechanics tells us that the initial excitation is now shared between the atom and the cavity, each of them being ‘half’ in the ground and ‘half’ in the excited state. In other words, the

\(^6\) The photoelectric effect consists in the emission of electrons from a metallic surface under illumination. Van Lenard and Millikan showed that electron emission only occurs for optical frequencies above a minimum threshold, indicating that energy is exchanged in quanta.
system is in a coherent superposition of the states: {atom in excited state, no photon} and {atom in ground state, one photon}. As there is a single excitation in the system, a measurement on one of the two will instantaneously determine the state of the other, independently of the physical distance between the two (which can be tens of km if the photon is propagated in a fiber). We then say that the atom-photon system is in an entangled state. If the photon interacts with another atom in a separate cavity, entanglement between two separated atoms can be established. Of course this non-local instantaneous correlation contradicts our physical intuition, which is based on the macroscopic observation that distant objects do not interact instantaneously. This non-local character of the theory, which is applicable to many different physical systems, triggered Einstein’s conclusion that quantum mechanics cannot be a ‘complete theory’ [11] – nevertheless, the predictions of quantum mechanics have been consistently confirmed by experiments. The study of atoms in cavities (‘cavity quantum electrodynamics’ or cavity QED) has offered a simple and elegant physical platform to explore the concept of entanglement, particularly between light and matter.

Apart from its fundamental interest, there are important practical applications of cavity QED. Quantum computing is based on the coherent manipulation of entangled systems (qubits). Whatever physical implementation (charge, spin...) is used for the qubits, there will always be the need to communicate qubits between physically separated parts of a computer, or nodes of a network. Such communication can only be realized with photons. Coherently mapping a

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**figure 4**

Left: Schematics of a cavity QED experiment, consisting of an atom coupled to the optical mode of a cavity. Right: Electron microscope image of a photonic crystal cavity. The optimized position of a QD at the cavity center is schematically indicated in red.

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7 It can be shown that this instantaneous correlation cannot be used to transmit information at a speed greater than the speed of light, and therefore does not violate special relativity.
matter-based qubit into a photon, as can be realized in a cavity, is therefore an essential part of any quantum computing system. Additionally, cavity QED offers a unique possibility of performing nonlinear quantum operations on photonic qubits, i.e. it could potentially provide the nonlinearity needed for quantum gates in a photonic quantum computer. This nonlinearity at the single-photon level is a direct consequence of the strong coupling between atoms and cavity field: as the field does not just produce a perturbation, but rather changes the energy structure, the atom’s response becomes nonlinear.

While many exciting experiments have been performed on atoms and ions in macroscopic cavities, any practical application of cavity QED to information processing should have a solid-state implementation. In this respect, semiconductor quantum dots (see above) represent a very convenient system, as they have an atom-like energy structure, can have large coupling rates with light, and are compatible with standard semiconductor technology. The challenge however lies in the fabrication of low-loss microcavities integrated with the QDs, and in the control of QD interaction with the cavity mode. Substantial progress has been realized in the last few years in the fabrication of low-loss microcavities, for example with photonic crystal (PhC) structures (see right part of Fig. 4). A photonic crystal is a crystal for photons, i.e. a periodic arrangement (in one, two or three dimensions) of materials with different refractive indices, with a period such that reflections from the different interfaces interfere constructively, giving a very high reflectivity (> 99.99% can be achieved). Light can then be trapped in a sub-µm-sized cavity between the mirrors, for a time as long as 1 ns [12] (note that in free space light would propagate over 30 cm in the same time). Ideally 3D PhCs would be needed for complete confinement in the three directions, however these are exceedingly difficult to fabricate, and in most cases a combination of 2D PhCs and conventional waveguiding in the remaining direction is used. PhCs can be fabricated by drilling periodic arrays of holes (shown in black in Fig. 4) in semiconductors, which allows the integration of QD-based, atomic-like emitters in the cavity, leading to cavity QED experiments in the solid state. This field is the subject of intensive research at the moment, with some first demonstrations of cavity QED effects [13]. However tremendous challenges must still be overcome, related to the very small spatial scales and fast timescales involved. In particular, optimizing the emitter–cavity interaction requires control of the QD position relative to the cavity with an accuracy of < 30 nm, and of their spectral separation to within < 0.1 nm. Additionally, dynamic control of their interaction within timescales of < 100 ps is needed to produce and control entangled states of the QD–photon system. This control may be achieved by applying ultrafast electric
fields to the QD, thereby shifting its emission energy, for example by the use of electrically-contacted cavity structures. These structures, whose fabrication is technologically challenging, will open the way to the investigation of cavity QED effects in the nanoscale and on ultrafast timescales, and will bring us a step closer to practical applications.
Applications and perspectives

The quantum nature of single photons, i.e. the fact that they can exist in a coherent superposition of states, makes them suitable for use as quantum bits in communication, computing and sensing. Here I will give the simplest example of an application in the communication field, but many more possibilities exist and are being investigated. ‘Quantum cryptography’, or more precisely quantum key distribution (QKD), is a technique for the exchange of cryptographic keys (i.e. secret sequences of random bits), which relies on coding the bits onto single photon pulses. The idea is illustrated in Fig. 5 (an extensive description can be found in Ref. [14]). Two partners (for example a bank and a customer), traditionally nicknamed Alice and Bob, want to establish a secret key to be used for further coding of a secret message (for example, a credit card number). To do this, Alice generates a random series of bits and sends them to Bob as light pulses, each containing at most one photon, along an optical fiber. The bits can be coded in any physical property (polarization, phase, time/position etc.) of the photons – here for simplicity we will assume that polarization is used, although in practice phase or time would rather be used in fibers. For example, the bit 0 (1) is coded as a horizontally (vertically) polarized photon. At other end of the fiber, Bob measures the photon polarization (for example using a polarizing beam splitter and two detectors) and reconstructs the bit value. Note that in most cases the fiber loss is not negligible, and a large fraction of the photons are lost and do not get to Bob. However this is not a problem for the purpose of exchanging a key8: at the end of the exchange Bob can tell Eve (using a public channel) which bits of the sequence he received, so that only these bits will form the key. As single photons are used, a potential eavesdropper (Eve) cannot ‘listen’ to the key exchange by diverting and measuring a part of the pulse, as she would do on a traditional communication channel. Indeed, if Eve measures a photon that bit will not get to Bob and will not be part of the key. However, in this simple scheme Eve still has the possibility of measuring the bit and sending another photon to Bob with the corresponding polarization. To prevent this type of ‘intercept-resend’ attack, Alice uses two different basis sets and she randomly chooses one of the two for coding each bit.

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8 In contrast, it is clear that single photons cannot be used to send a message, as any lost bit would represent an error.
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For example, in half of the cases she uses the \{0° (horizontal) / 90° (vertical)\} basis, and in the other half the \{+45°/-45°\} basis. Bob also randomly chooses between two sets of polarization analyzers. Note that measuring a 45°-polarized photon in the \{0°/90°\} basis yields either outcome with equal probability. At the end of the exchange they publicly declare the sequence of polarization sets used (but not the bit values), and discard the bits for which two different polarization sets were used. As Eve does not know in advance which polarization set is being used for each bit, if she carries out an intercept-resend attack she will choose the wrong polarization set on half of the bits (for example, horizontal/vertical while the photon was 45°-polarized). As a consequence, she will measure and retransmit a horizontally or vertically polarized photon with equal probability.

If Bob chooses the same polarization set \{+45°/-45°\} as Alice, he will measure the photon retransmitted by Eve in the wrong basis, and thus get a random result. In half of the cases, this will produce an error in the key (e.g. Alice sent a 1 (+45°) and Bob measures a 0 (-45°)). Alice and Bob can therefore check the possible presence of Eve by monitoring the error rate: if the latter is lower than a certain threshold, they can determine that nobody has interfered with the key exchange.

Note that this protocol is based on the fact that a photon is a qubit which can exist in any polarization state, i.e. in any coherent superposition of the basis states. As any measurement projects the qubit in the measurement basis (a fundamental postulate of quantum mechanics), it is impossible for Eve to determine its polarization if she does not know the correct basis.

It may be tempting to propose another strategy for Eve: amplify the photon (e.g. by stimulated emission in an optical amplifier) to get multiple copies (clones) of it, and then measure one of the resulting photons. However, the ‘no cloning’ theorem
of quantum mechanics [15] shows that perfect copying of quantum states is impossible, as it violates the fundamental postulate of linearity. For example in the practical case of an amplifier, amplifying the photon introduces noise (by spontaneous emission, which for one incident photon is as likely as stimulated emission), which in turn induces errors in the key exchange and can be detected.

The most attractive feature of QKD, as compared to traditional cryptographic protocols based on computational complexity, is that security is guaranteed by the laws of physics9, and not by the limited computing power available to the eavesdropper. For this reason, it has grown from a scientific curiosity into an application field, with several companies (e.g. idQuantique, MagiQ Technologies, SmartQuantum) commercializing turnkey systems. However, it suffers from limitations related to its very fundamental principle: the use of single-photon qubits as the information carriers. Indeed, single photons are difficult to generate and to detect, as discussed in the previous sections. Most importantly, single photons cannot be amplified, as mentioned above, which implies that photon losses in fibers cannot be compensated. As the fiber length is increased, fewer and fewer photons will reach Bob, until the transmitted photons can no longer be distinguished from the detector's dark counts, and a secure key cannot be exchanged. For current QKD systems, the maximum link length is limited to \( \approx 100 \) km when commercial avalanche photodiodes are used, and to \( \approx 200 \) km by using the ultra-low-noise SSPDs described above. To go well beyond this limit, a radically different approach based on the use of ‘quantum repeaters’ will have to be used. Quantum repeaters are analogous to the classical repeaters used in optical communications: intermediate stations within the QKD link, where the information is ‘purified’ to compensate for the degradation during transmission. Practical implementations of quantum repeaters [16] will probably consist of small optical circuits including a source of single or entangled photons, some linear optical devices, single-photon or photon-number-resolving detectors, and ‘quantum memories’ able to store photonic qubits for very long times (ms or even seconds). For practical applications, these devices will have to be integrated into a compact photonic chip able to perform all these functions. The vision of ‘quantum photonic integrated circuits’, for quantum repeaters as well as for small photonic quantum computers, is one of the driving forces for the research into solid-state quantum devices carried out at TU/e and other laboratories worldwide.

9 In practice, proving the security of a QKD protocol against any type of attack can be quite complex, and in most cases requires some (very reasonable) assumptions to be made about the technology available to the eavesdropper.
After this brief description of my research interests, I would like to devote a few words to how research (and education) can be carried out, and particularly the international aspects. During most of its development modern science has surpassed national borders, seeking universal truths, independent of culture, language and politics. The mutual isolation of scientific communities due to war or politics (e.g. during the cold war) has only resulted in a delay in scientific progress and loss of productivity: so many important results obtained in the former Soviet Union block have long remained ignored and been independently rediscovered, because they were published in Russian and not publicized in conferences.

Based on these considerations, and with the aim of improving coherency and effectiveness, European political institutions have, ever since their establishment, aimed at integrating research activities in Europe by promoting the exchange of researchers and funding joint research projects. My personal story and professional development is a direct result of these efforts and a clear example of their effectiveness. Born and educated in Italy, I carried out my Master’s and PhD theses in France with the help of two European mobility grants, and after a short postdoctoral stay in the United States, I pursued my career successively in Switzerland, Italy and now in the Netherlands, always with direct or indirect support from EU research funding. I have past or ongoing collaborations with over twenty laboratories in seven European countries, and over half of my publications are the result of international collaborations. Generally speaking, seven generations of EU Framework Programmes (FPs) have succeeded in establishing very high levels of collaborations, exchanges and contacts among European laboratories. Nevertheless, it is also interesting to explore the failures and limitations of EU (and international) research policies.

A first issue has been the focus on applied research: until recently, EU funding was reserved for projects with clear application-oriented goals, and in practice industrial participation was a prerequisite (with the very limited exception of the ‘Future and Emerging Technologies’ program). This strategy has recently been partly revised, and the newly established European Research Council (ERC) aims at providing funding opportunities for fundamental research. Indeed, it would not make sense to promote integration only for applied research, leaving a
patchwork of independent and isolated fundamental research activities in member states.

Secondly, EU research funding has systematically been of a short-term nature (the typical project duration is three years), aiming at establishing focused collaborations limited in time. Starting from FP6, a broader goal of ‘integrating’ the research activities of different European institutions on a longer, possibly semi-permanent timescale has been pursued. To this aim, the new funding instruments of ‘Integrated Projects’ (IPs) and ‘Networks of Excellence’ (NoEs) have been established, focusing more on the integration and less on the technical objectives. The success of the new strategy is, in the opinion of many researchers and EU project officers, quite limited. The main problem is the fact that, while a commitment towards long-term integration is requested, funding remains limited to three or four years. As a result, if two or more laboratories decide to organize their structure and strategy in order to share resources and achieve better effectiveness, after three years they are out of EU funding. Nor can they easily apply for national funding, since they cannot any more carry out research projects independently because of their integration (national funding schemes practically never allow funding of international collaborations). If real, long-term integration is to be pursued, the related EU funding should also be of a long-term duration (5-10 years, possibly subject to re-evaluation). In addition, national funding agencies should agree on schemes for mutual funding of international collaborations, particularly if the institutions involved have taken steps towards long-term integration. Research institutions can also take direct initiatives to establish preferential and long-term networks between themselves – the ongoing contacts between TU/e, TU Munich and TU Denmark in the field of nanoscience represent a good example. However, these initiatives must always be substantiated by real research funding, otherwise they remain formal and do not bring real integration.

Another limitation of the past, and to some extent present, EU research policy is the tendency to remain constrained to the European borders. Basically, no funding opportunities exist for joint projects between laboratories in Europe, the United States or Japan. For example, the only contacts with our very active US competitors are through conferences. This tends to create inbreeding, which is easily seen in some fields where EU and US research directions are almost orthogonal, or temporally shifted (in general, EU following with a few years’ delay). While physical distance and different industrial and economic policies make the level of possible integration with US institutions more limited than
within Europe, increased contacts, collaborations and joint roadmapping initiatives are highly desirable. The establishment of dedicated instruments or agencies for funding joint research projects is possible and should be pursued. The same applies to other countries where the level of activities in science and technology is high (e.g. Japan, Australia) or rapidly increasing (e.g. China, India). Also in this case, ambitious goals should always be accompanied by real funding.

The above indications also, and even more strongly, apply to education. Europe needs the most talented human resources to become more competitive in science and innovation. The first priority obviously goes to promoting science among young European generations, providing them with the best scientific education, and offering working conditions that will keep the best brains in European industrial and academic institutions. However this is often not sufficient, particularly in rapidly developing fields where the inflow of young European scientists cannot keep pace with the increasing demand. Looking at the US example, a key factor in the successful scientific and technological development of a country is its ability to attract high potential, highly educated young individuals from abroad. This can be done by providing attractive working conditions, facilitating immigration procedures and establishing instruments for promotion and selection in the countries of origin. While the US has a long tradition in this field, Europe and European institutions have so far made little effort to attract potential students and graduates, particularly from countries such as India, China and Iran, which in terms of population and quality of their educational systems have an immense reservoir of human potential. On the contrary, formal obstacles such as long visa delivery times often make the selection and hiring of graduates and undergraduates from these countries very difficult. Strict immigration policies should never apply to science graduates, for whom a preferential channel must always be present. Moreover, if we want to compete with universities such as Berkeley and Harvard in the quest for the best students, we need to promote our universities in their countries of origin, select the students locally and offer financial incentives to facilitate their relocation. This cannot be done by a single research group, but rather at the level of the university, or even better that of a consortium of top universities. More generally, Europe should provide specific instruments for promoting student mobility and exchanges with external countries, as it has done in the past within its own borders. This ‘brain gain’ does not necessarily result in a brain drain for developing countries, if adequate instruments are established for the re-integration of the researchers in their home countries. On the contrary, it contributes to the promotion of young generations of leaders with international experience and culture, and ultimately to progress and peace.
I would like to take this opportunity to thank the very many people who have helped me to develop professionally and personally. My thoughts go first to my teachers, who made me love the field of photonics: Prof. Gaetano Assanto, who taught an inspiring course of Optoelectronics in my final year of Engineering, and Prof. Emmanuel Rosencher, my PhD supervisor. Emmanuel, your passion, physical intuition and enthusiasm have given me an outstanding example of scientific leadership. During my Master’s and PhD work I also greatly enjoyed the support and guidance of my co-supervisors Dr. Jean-Yves Duboz and Prof. Vincent Berger. I am grateful to my supervisors during the subsequent postdoctoral appointments, Prof. Larry Coldren and Prof. Marc Ilegems, from whom I learned much science, but also management skills, and who gave me an uncommon level of independence. Marc also helped me a lot in my transition to an independent researcher with wise advice, support and access to equipment. After establishing my first independent group in Lausanne, I benefited immensely from the support of the institute’s director Prof. Benoit Deveaud: thank you so much for trusting me and giving me the means to fly. Before and after arriving at TU/e, I enjoyed the support and collaboration of all the members of the Photonics and Semiconductor Nanophysics group, and particularly of Prof. Paul Koenraad – Paul, working with you is a great pleasure. A final thought goes to my former and present students and coworkers, who did the real work in the lab since I got stuck in management, administration and teaching: Alexander, Blandine, Carl, Cyril, Christelle, Lianhe, Laurent, Francesco, David, Philipp, Nicolas, Matthias and Saedeeh, many thanks, not only for your outstanding work, but also for sharing the joy and pain of research in a collaborative and friendly atmosphere. Finally, my professional development was also made possible by the support and continuous encouragement of my family and of my wife Susanne. Through their example, my parents taught me to work hard and to be ambitious, but also to establish good working relations. They encouraged me to pursue my dreams, even when this implied that I would be far from them – and never complained about that. Susanne, your trust, love and support are precious to me every single day. I am not sure how I managed to convince you to leave your mountains – this has been my biggest accomplishment! I am looking forward to a long and happy life together.

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<td>For a review see: F. Rieke and D.A. Baylor, Reviews of Modern Physics, 70, 1027 (1998)</td>
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Curriculum Vitae

Prof.dr. Andrea Fiore was appointed full-time professor in Nanophotonics at the Department of Applied Physics of Eindhoven University of Technology (TU/e) on 1 October 2007.

Andrea Fiore (1970) graduated in Electrical Engineering (1994) and in Physics (1996) at the University of Rome ‘La Sapienza’. He gained his PhD in Optics (1997) from the University of Paris XI-Orsay, with a thesis on nonlinear optics in semiconductor heterostructures. He has worked at Thales Research and Technology (Orsay, France), at the University of California, Santa Barbara, at the Italian National Research Council (Rome, Italy), and at the Ecole Polytechnique Fédérale de Lausanne (Switzerland). In October 2007 he was appointed full professor at TU/e. His research interests are in the physics of nanophotonic devices, particularly quantum dot lasers, single-photon sources and superconducting single-photon detectors. He coordinated several national and international projects, including the EU-FP6 ‘SINPHONIA’ project. In addition, he has co-authored over 100 journal publications and three book chapters, and has given around 30 invited talks at international conferences.

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