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Light – Matter Interaction on the Nanoscale

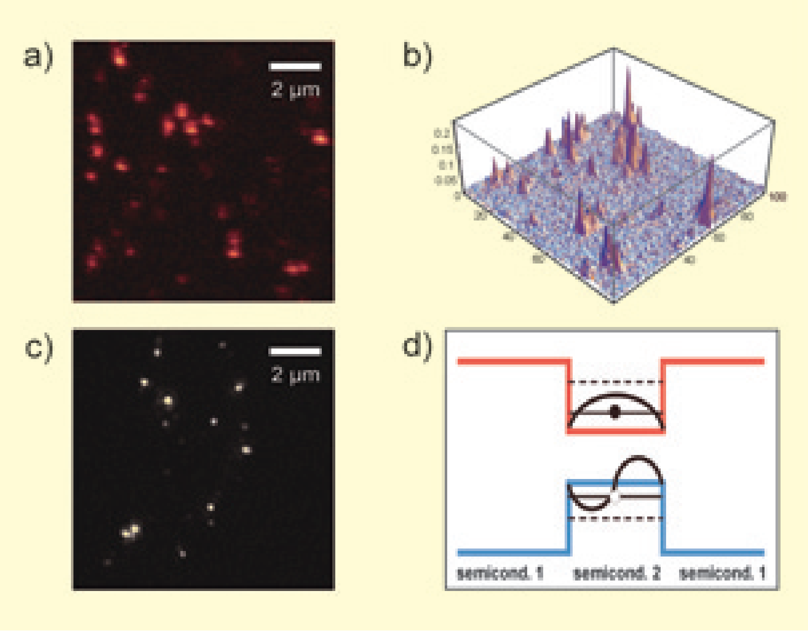
In 1959 the physicist Richard P. Feynman held a famous talk entitled »There's plenty of room at the bottom«. In this talk he concluded that there is no physical limit on miniaturization that prevents to make devices from single molecules or atoms. At that time the technology was far from that limit, however, todays nanotechnology allows indeed to detect and manipulate single quantum particles.

A specific field in nanoscience is nanooptics where the interaction between light and matter is investigated on the length scale of nanometers. There are two possible approaches to enter the nanoworld. The first is a bottom-down approach where one tries to assemble devices from single atoms or molecules, i.e., starting at the very bottom in Feynman's sense. The other approach, the top-down strategy, is to begin with ordinary bulk material, but to machine smaller and smaller structures.

Fig. 1 shows an example for these two strategies: Each of the bright spots in the scanning microscope image in (a) and (b) corresponds to a single molecule which was dispersed from solution on a glass slip and excited with laser light. Manipulation of these emitters can be performed using modern scanning microscope techniques, such as atomic force microscopy (AFM) or scanning near-field optical microscopy (SNOM). The image in c) shows fluorescence from single quantum dots. Quantum dots are tiny semiconductor crystals, where the charge carriers (electrons and holes) are trapped inside a box-like potential (see Fig. 1d). The fluorescence light due to radiative recombination of electrons and holes has discrete spectral lines. This similarity to resonance fluorescence from single atoms led to the denotation »artificial atoms«. Now, the great advantage of these artificial atoms is that their properties can be taylored to some extend by modifying the confining potential (the box), which is a main prerequisite for possible applications.

Fig. 1

(a) and (b): Scanning confocal microscope images of single dye molecules.
(c): Fluorescence image of semiconductor quantum dots.
(d): Schematical potential of electrons and holes in a quantum dot (semicond. 2) surrounded by a different semiconductor matrix (semicond. 1).



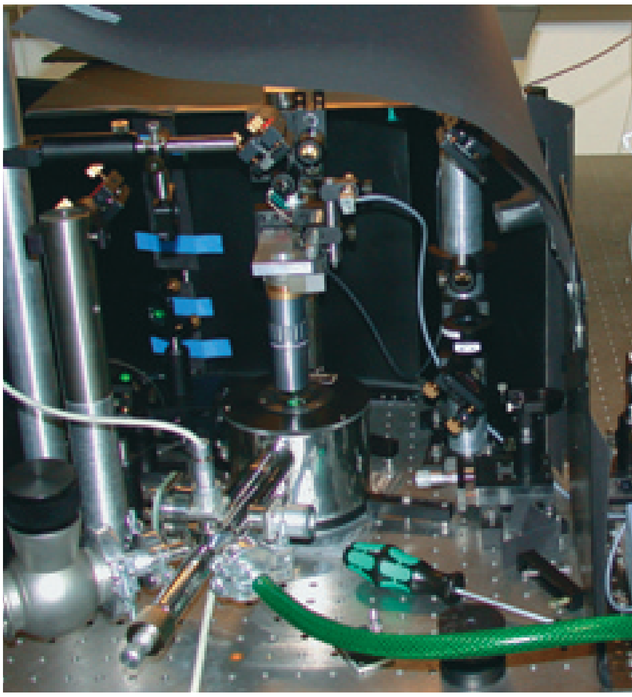


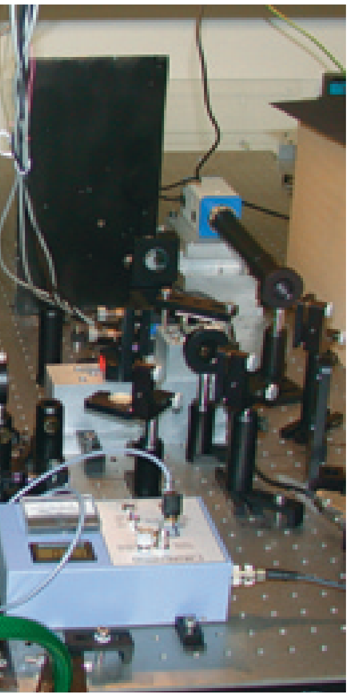
Fig. 2

Photo of the experimental setup. On the left one recognizes a cylindrical cryostat required to cool the sample to about 4 Kelvin. A microscope objective from above collects the photons which are sent to the HBT-correlator.

Single photon generation

The light which is emittted from a single quantum emitter such as an atom, a molecule or a quantum dot is inherently quantum in nature. Obviously, the radiative recombination of a single hole and a single electron in a quantum dot can produce a single light quantum or photon only. Soon after the introduction of quantization of the radiation field by Planck in 1900 or by the concept of photons by Einstein in 1905 there were experimental attempts to demonstrate this quantum nature directly. The first naive approach was to attenuate ordinary light or light pulses so much that they contained less than a single photon on the average in each pulse. However, when performing experiments at this extremely low level of the intensity (as done by Taylor in 1909 [1]) no difference to classical light was observed. It took more than six decades until the direct quantum nature of light was observed [2] in experiments which measured the photon statistics, a property related to the intensity of light rather than the amplitude as in interferometric measurements.

There is a striking difference between the photon statistics of classical light, e.g. thermal light emitted from a light bulb, and quantum light emitted from a single quantum emitter. In thermal light the photons arrive in bunches which reflect classical intensity fluctuations. In light from a single quantum emitter, however, there is a peculiar difference: If one detects a photon one knows with certainty that the emitter is in its ground



state, i.e., it is now not »ready« to emit a second photon immediately. A certain time is required to reexcite the emitter before it can emit again. Thus, photons tend to be separated by a certain time interval, they are antibunched. Presentday detectors are capable to detect single photons. In measurements of the intensity autocorrelation function a so-called Hanbury Brown-Twiss (HBT) setup is used, where light is send to a beam splitter and is subsequently detected by two single photon counters. A detection event of a single photon by one detector starts a clock which is stopped by the detection of a second photon by the other detector. A normalized histogramm of many of these time intervals gives the autocorrelation function. This function has to be zero at zero time delay because the detection of a single photon cannot be followed by a second detection event immediately. This minimum directly proofs the quantum nature of light.

We performed experiments with the light emitted from a single quantum dot [3]. A photo of our experimental setup is shown in Fig. 2. It consists of a microscope where excitation light from a laser is focussed to a small spot on a sample containing only a few quantum dots. If the spatial resolution is good enough only a single dot can be excited. Fluorescence from the dot is collected by the same microscope objective and sent to an HBT-correlator. Fig. 3 shows the measurement for continuous wave (a) and pulsed (b) excitation. The measured correlation function for continuous wave excitation shows a very pronounced minimum at zero time delay between detection events as predicted from quantum theory. This outcome of the experiment cannot be explained by a classical theory. Fig. 3 (b) shows a measurement for pulsed excitation. The correlation function now has of a number of peaks seperated in time by the inverse of the pulse repetition frequency. The peak at zero time delay is completely suppressed. This shows that the light is a regulated train of single photons with a well defined time separation.

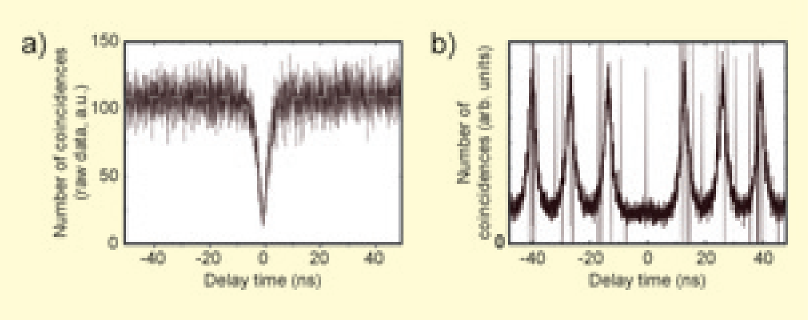


Fig. 3
Measured autocorrelation function of light from a single quantum dot under (a) continuous wave and (b) pulsed excitation.

Nano-Optik
Gegenstand unserer Arbeit ist die Erforschung der Wechselwirkung von Licht und Materie auf der Nanometerskala. Auf dieser Größenordnung treten quantenphysikalische Effekte auf, und selbst die klassische Physik verhält sich ungewohnt. Wir versuchen, diese nanooptischen Effekte zu verstehen und zu testen, ob sie für neue Anwendungsmöglichkeiten genutzt werden können. Schwerpunkte unserer Arbeit sind die Quanteninformationsverarbeitung, die Eigenschaften von Licht in eingeschränkter Geometrie, sowie die Nano-Manipulation von Quantenemittern, u.a. zur Entwicklung nanokompositer Funktionselemente und neuer Mikroskopieverfahren.

Quantum information

What is now the application of quantum light emitted from single quantum dots? As described above the light emission in quantum dots occurs »photon by photon«. Thus one can envision a device where pushing a button leads to emission of a single photon. This principle is the basis of single photon sources [4] which have a number of important applications. One possible application is an intensity standard. If a single photon source is driven by a periodic excitation source of fre-

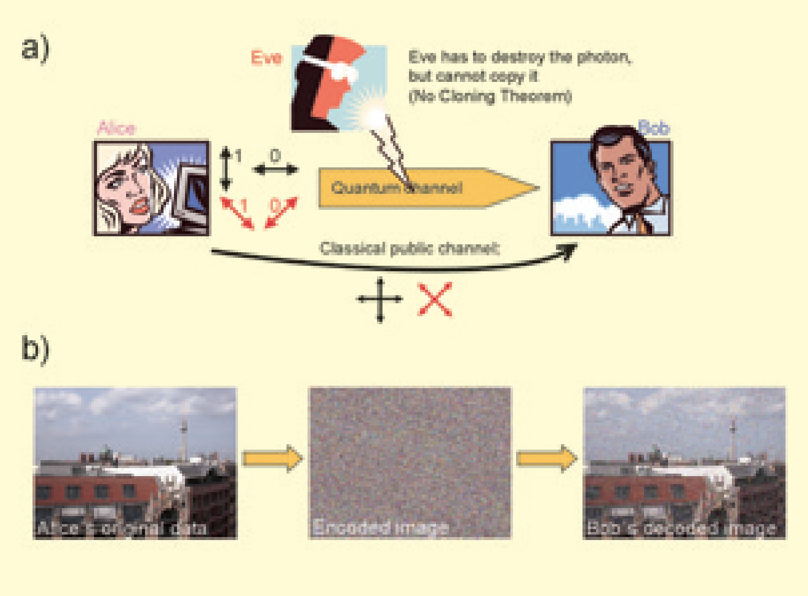


Fig. 4
(a): Illustration of quantum cryptography. Alice and Bob communicate over a quantum channel where information is encoded in the polarization of single photons.
(b): Experimental results. Information (a photograph) was encoded and decoded using a secret key which was transmitted over a quantum channel. An error rate of appr. 10% produces some random pixel noise in the encoded image.

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quency f then the power of the emitted light is exactly $P=h\nu f$, where $h\nu$ is the energy of a single photon of frequency ν.

Another application is quantum information processing (QIP). In QIP information is encoded in bits (0 or 1) similar as in its classical counterpart. The striking difference, however, is that a quantum bit or qubit can be in a coherent superposition of 0 *and* 1. This quantum effect leads to fundamentally different properties of devices using qubits. Quantum computers would have superior properties compared to classical computers and could solve certain problems exponentially faster. Quantum computers using qubits encoded in the two polarization states of a single photon (0=vertical, 1=horizontal), so-called flying qubits, have been proposed [5].

Here, we would like to focus on a different task in QIP namely quantum cryptography [6]. The problem is to transmit a secret key from a sender called Alice to a receiver called Bob (see Fig. 4 (a)). How can they avoid beeing listened to by an eavesdropper? The solution to this problem relies on the very quantum nature of the single photons used for information exchange. It is impossible to measure the polarization of a single photon without disturbing it, i.e. projecting it on a certain basis. At the same time the laws of quantum physics do not allow to make an exact copy of an unknown quantum state (no-cloning theorem). Given these two features each attempt by an eavesdropper to listen to the information exchange between Alice and Bob would inevitably lead to an enhanced error rate which Alice and Bob would easily notice. As there is no way to bypass the laws of physics quantum cryptography is absolutely secure.

We used our single photon source to demonstrate secure data transmission [7]. Information (in our case a photograph showing a view out of our office window) was encoded in the polarization state of single photons and sent over a distance of a few ten centimeters to a receiver where it was encoded. Fig. 4 (b) shows the experimental results. Quantum cryptography is the most advanced quantum technology so far. Free space transmission over several tens of kilometers using real single photon sources has been demonstrated and first commercial systems are available.

Group members in 2004
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Nanophotonics

Single photon generation is but one example for experimental nanooptics. In other research activities in our group we use techniques developed in scanning microscopy to manipulate nanoparticles in order to control their interaction with nanostructured material or with each other [8,9]. Apart from more fundamental research such as the conversion of stationary qubits (needed in a quantum computer) to flying qubits (needed for transmission) there are a lot of interesting applications ranging from optical microscopy with molecular resolution towards ultrasensitive detection in optical (bio-)sensors.

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