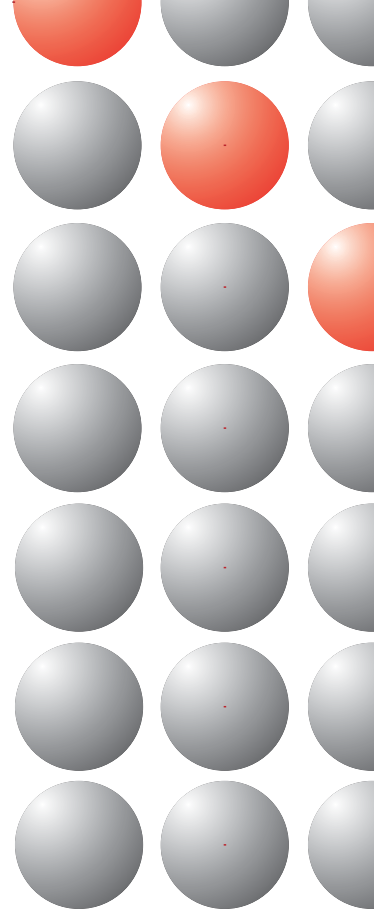Vladan Vuletic

Generating Single Photons on Demand

In optical signal transmission, binary signals are encoded in pulses of light traveling along optical fibers. An undesirable consequence is that if somebody taps into the system and splits off a small portion of the light pulse, he has complete access to the signal while remaining virtually unobservable.

THE QUANTUM NATURE OF LIGHT, that is, the fact that light consists of individual photons, prevents, however, the extraction of a small fraction of a weak pulse. If each bit of information is encoded, *e.g.*, via the light polarization, in a pulse that consists of exactly one photon, then the eavesdropper must divert the whole pulse, which is easily detected at the receiving end. Neither can the intruder copy the state of the photon into his own photon and measure the polarization state of the replica. The latter approach is prevented by the so-called no-cloning theorem of quantum mechanics: it is impossible to copy the unknown polarization state of a single photon without modifying the original in a noticeable way. The impossibility to both measure and preserve a quantum state is the principle behind quantum encryption, *i.e.*, encryption protected by the laws of quantum mechanics.

In order to be quantum-secure, the light pulse carrying the bit must never contain more than one photon, otherwise the eavesdropper could divert one of the photons and measure its polarization. To generate one photon on demand, however, is surprisingly difficult. The simplest approach is to attenuate a light pulse to a
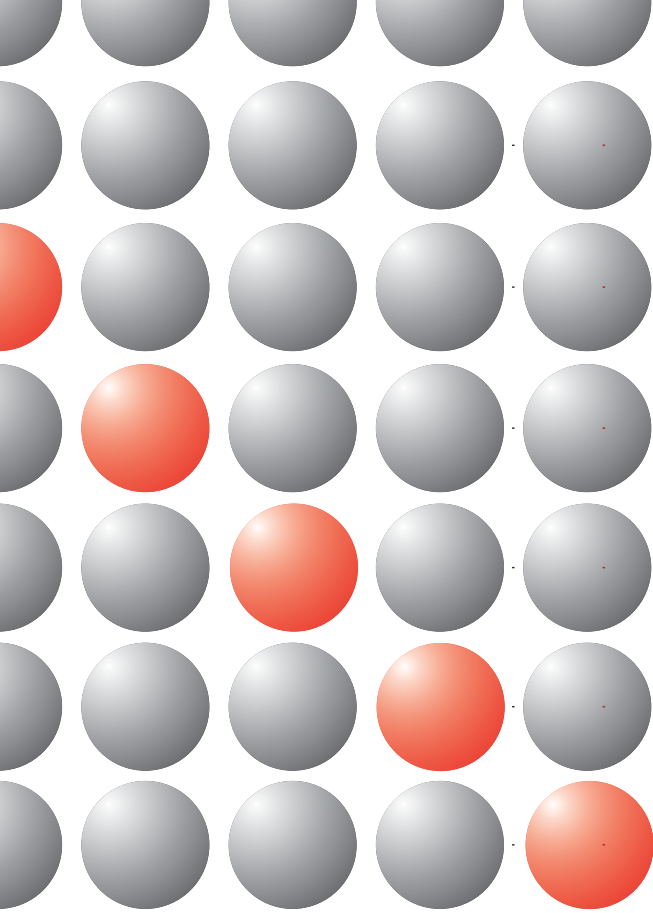
level where it contains less than two photons on average. However, the *actual* number of photons in any given pulse is intrinsically random and can exceed the average number. While undesired two-photon pulses can be suppressed by further attenuating the light, this comes at the expense of the pulse rarely containing any photon at all, *i.e.*, at the expense of a much reduced signal transmission rate. Quantum encryption at high rate, as well as over distances exceeding the absorption length of optical fibers[1], can be accomplished with a single-photon source, *i.e.*, a light source that generates exactly one photon per pulse.

In order to generate a single photon, one may consider using a single microscopic emitter, *e.g.*, a single atom. When an atom makes a transition between two internal states, energy conservation ensures that it will emit exactly one photon with a frequency that corresponds to the energy difference between the two atomic states. In practice, this is conveniently accomplished as a two-photon transition between two stable ground states g_1, g_2 of the atom via an unstable excited state e (*Figure 1*), since one can start the emission process by applying a laser beam to transfer the atom from g_1 to e, from where it can decay to the other stable state g_2 by emitting one photon. In this way, exactly one photon can be generated, albeit in a random direction. However, in practice one can collect light only in a finite and small solid angle, resulting again in a random number of *collected* photons. A useful single-photon source must emit into a well-defined direction.
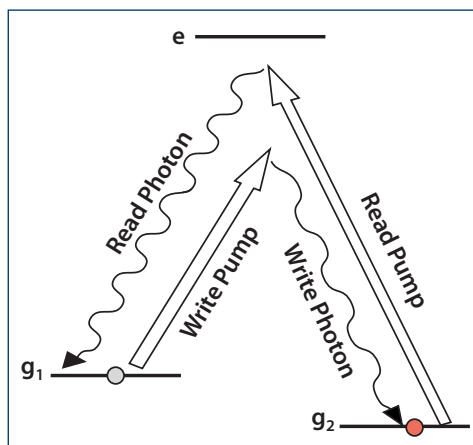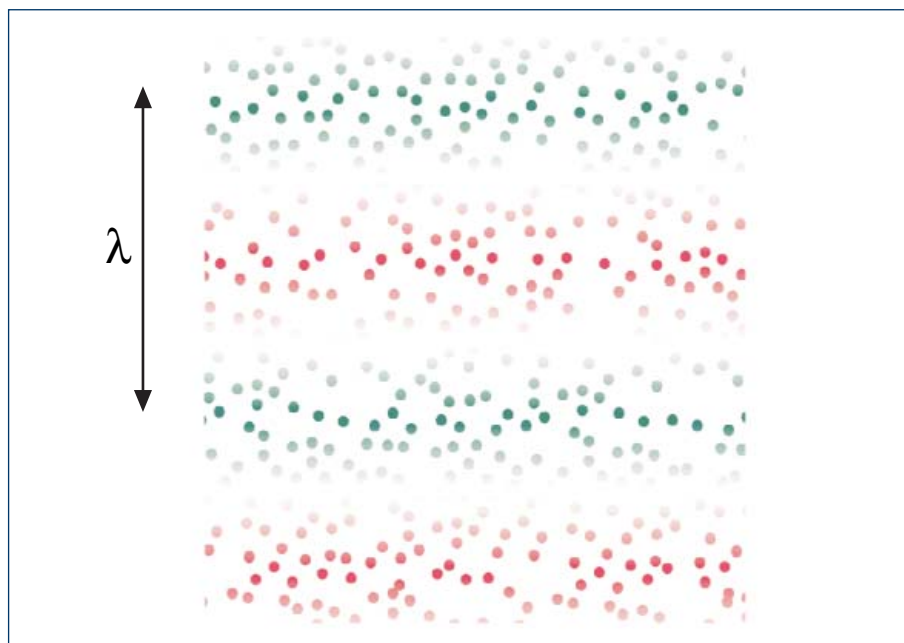
For classical radiation, an array of antennas can be arranged to produce highly directional emission. For correctly chosen phases between the antennas, the emission into one particular direction can be strongly increased by constructive interference between the waves from the different emitters. The same principle applies to a sample of radiating atoms (see *Figure 2*): if the correct relative phase between the atomic oscillators can be imprinted onto the sample, the light emission from the sample can be very directional, as in a laser.

Quantum mechanics allows one to prepare an array of emitters that generates a single photon in a well-defined direction. While the individual atoms oscillate similar to antennas in a phased array, producing a highly directional emission pattern, there is only a single photon stored in the system. The many-atom state that stores the photon is strongly correlated: on the one hand, it is impossible to predict which atom is excited; on the other hand, if a certain atom is measured to carry the excitation, none of the other atoms will be found to carry it. The atoms in this state, a so-called entangled state, "know about each other," and collectively share the single photon (*Figure 3*).

The entangled state, where exactly one photon is simultaneously and collectively stored in a million atoms, is generated by measurement. Starting with an ensemble of many atoms prepared in the state g_1 (see *Figure 1*), a weak light pulse ("write pump") is applied that excites an atom to an unstable excited state e, from where it can decay to the state g_2 by emitting a photon. If one such emitted photon, labeled "write photon" in *Figure 1*, is observed on a single-photon detector, we know that one atom in the sample must have made the transition, but we cannot, even in principle, know which atom it was. The detection of a single write photon produces an array of atomic oscillators similar to the one depicted in *Figure 2*. The equivalent of one photon is stored in the system in the form of one atom

that has been transferred from the state g_1 to the state g_2 in the process. The source is now armed.

Subsequently, a single photon can be generated on demand by applying a laser beam ("read pump," see *Figure 1*) to restore the original state by transferring the atom from g_2 to the excited state e, from where the atom can decay to g_1 by emitting a photon ("read photon"). For an appropriately chosen geometry, this read photon will be emitted into a well-defined direction, as necessary for a useful single-photon source. The condition for directional emission by the array is equivalent to the requirement that the original state, including the momenta of all individual atoms, be restored. This requirement can be viewed as a consequence of a general "which path" argument in quantum mechanics: processes that can occur via different pathways (different atoms emit-

ting the photon) interfere only if it is impossible to determine which path is taken. Otherwise, the which-path information destroys the interference pattern. If, by measuring each atom's velocity we could determine which atom carried the excitation, the interference leading to directional emission would not occur.

Similarly, thermal random motion of the atoms eventually destroys the interference. If the individual atoms constituting the array of phased oscillators randomly move a distance comparable to a wavelength of the imprinted pattern
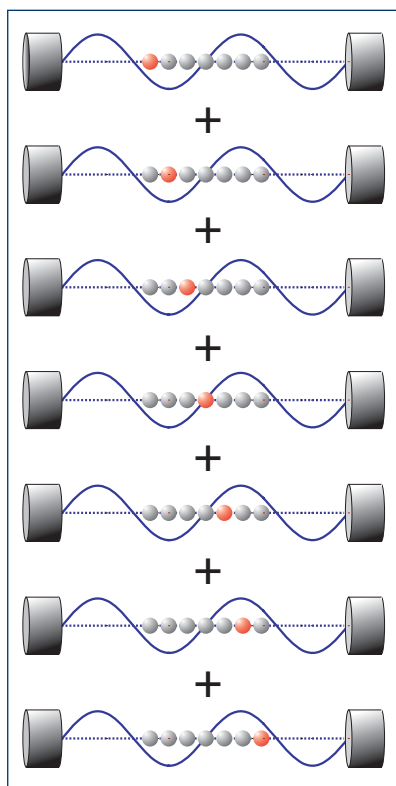
(see *Figure 2*), the grating will wash out and collective emission will not occur. Thus the entangled many-body state has a finite lifetime that depends on the temperature of the atoms and the chosen beam geometry. The single photon must be generated within a certain time after the source has been armed.

We work with a sample of typically 100,000 cesium atoms, prepared by laser cooling to a temperature of thirty microkelvin (*Figure 4*). The sample is placed at the center of an optical resonator that serves to enhance the directionality of the source. We illuminate the sample by a weak laser beam (write pump, see *Figure 1*), which excites an atom to a state *e* from where it can decay by emitting a photon into the resonator. The photon eventually leaves the resonator through the partially transmitting mirrors, is collected into an optical fiber, and delivered to a photodiode that can detect a single photon. After a variable delay time, the sample is illuminated by the read pump beam counterpropagating relative to the write pump beam. If the phased-oscillator array is still intact, the sample will directionally emit exactly one photon into the resonator. This is the useful photon that for our experiment is registered on the same photodetector.

Figure 5 shows the measured write and read photons emitted by the sample, averaged over many repetitions of the experiment. For short times less than 1 μs, a large fraction of the single quantized excitations written into the sample (on the order of 50%) is recovered on the subsequent read pulse. Note that this corresponds to a very directional source, since the solid angle of the optical resonator mode is smaller than one part in 10^4. As the delay time is increased the number of read photons decreases, presumably due to the thermal motion of the atoms that washes out the grating. The longest measured entangled-state lifetime so far is 3 μs, which is the time it takes a laser-cooled atom to move a distance comparable to a period of the grating, on the order of 500 nm. In future, we will lengthen the entangled-state lifetime by using a smaller angle between the laser beams and the resonator, which will result in a longer-wavelength grating. The recovery efficiency can be increased to nearly 100% by using more intense beams.

An interesting feature of the system is that it allows one to superimpose different oscillator arrays (holographic gratings) in the same medium. Therefore it is possible to store and manipulate many quantized excitations simultaneously. This will allow one to explore and engineer various quantum-mechanical many-body systems. For instance, it should be possible to implement teleportation of quantum states, and possibly even quantum computation, in this highly non-classical system.

ENDNOTE

[1] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, *Long-distance quantum communication with atomic ensembles and linear optics*, Nature **414**, 413 (2001).

A German citizen, VLADAN VULETIC *was born in Pec, Yugoslavia, and educated in Germany. In 1992, he earned a Physics Diploma from the Ludwig-Maximilians-Universität München, and in 1997, a Ph.D. in Physics from the same institution.*

While a postdoctoral researcher with the Max-Planck Institute for Quantum Optics in Garching, Germany, Vuletic accepted a Lynen Fellowship at Stanford University in 1997. In 2000, he was appointed an Assistant Professor in the Department of Physics at Stanford and in June 2003 accepted an Assistant Professorship in Physics at MIT. He was promoted to Associate Professor in July 2004.