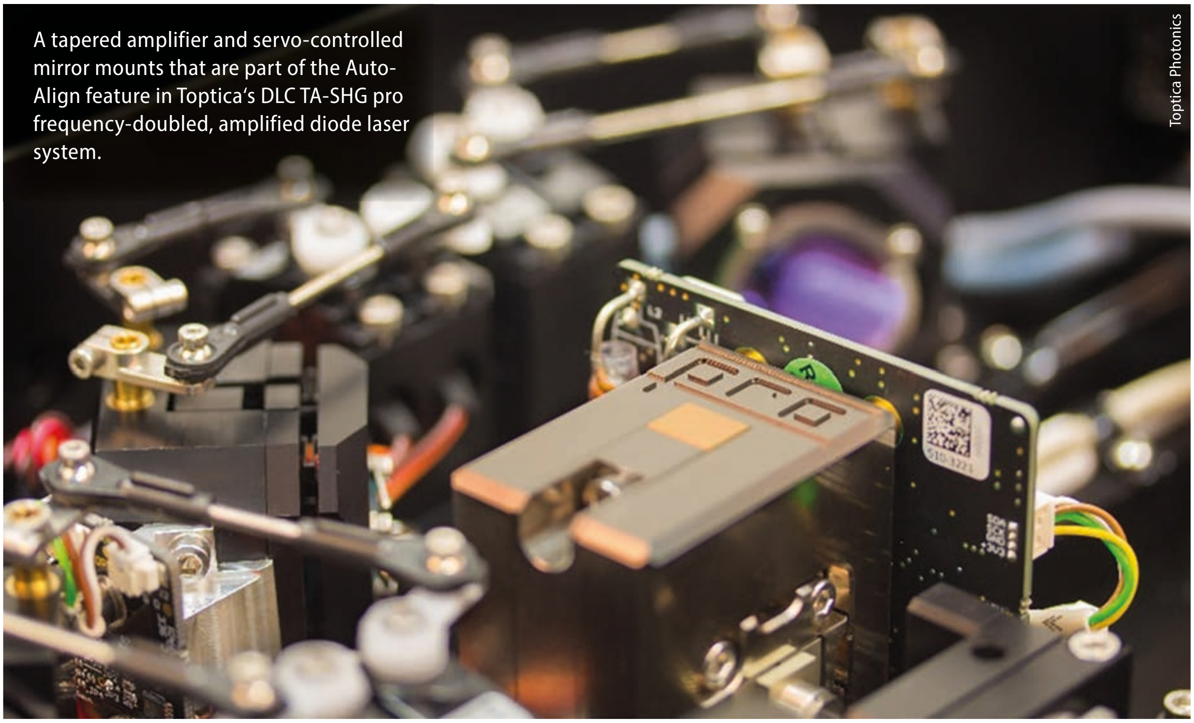

A tapered amplifier and servo-controlled mirror mounts that are part of the Auto-Align feature in Toptica's DLC TA-SHG pro frequency-doubled, amplified diode laser system.

Toptica Photonics

Talking About a Revolution

Through the transition from quantum mechanics to quantum technology fundamental physics turned into one of the hottest technologies today.

Stephan Ritter

Quantum physics is often considered weird, counterintuitive, and irrelevant at macroscopic scales. And yet, more and more people talk about it publicly, including politicians like Canadian Prime Minister Justin Trudeau. What has happened? Why is a theory that is about a century old suddenly in vogue when it is combined with the word technology? And what is meant by the second quantum revolution?

The short answer: it is because of the wealth of potentially revolutionary applications of quantum technologies. But let's step back and start from what has happened over the past decades. Undoubtedly, computers have revolutionized the way we live and work. This was enabled by groundbreaking achievements in several scientific and technological disciplines. The most fundamental one of them is quantum physics, where a better understanding of the laws at an atomic scale laid the ground for semiconductor devices. The laser is another prominent example of a device based on quantum mechanical effects. The processes underlying the laser are inherently interconnected with wave-particle duality – a central concept in quantum mechanics. The behavior of quantum objects is in some cases well described by treating them as waves, whereas sometimes a particle description delivers the potentially more intuitive explanation. Neither of them is sufficient and taking both too literally will lead to contradictions that hinder a complete understanding. This was obviously no obstacle to the laser quickly becoming a versatile tool: to transmit information, for material processing and inspection, for ranging and other metrological applications or for lighting and imaging.

The properties of light

But researchers not only explored applications. In fundamental science, they looked for answers to questions independently of immediate applications. They wanted to understand the nature of quantum systems better. Quantum optics, for example, deals with the properties of light from a quantum-mechanical perspective and in particular with its interaction with matter. One of the many questions is: in which aspects is the light emitted by a laser fundamentally different from the light emitted by a lamp? Obviously, light from a laser is well collimated, propagating in a single transverse electromagnetic mode. But light from a bulb can be spatially filtered as well. Laser beams are typically more intense than classical light beams, but that is not a qualitatively distinctive feature either. Lasers are typically coherent, and emit in a very narrow wavelength range. But the same applies to light from a thermal lamp that is spectrally filtered to an extremely narrow bandwidth. Was there not a more fundamental property, reflecting the quantum process of the light generation itself?

How to tell a laser from a lamp

An idea put forward and investigated by Hanbury Brown and Twiss in the 1950s was that intensity fluctuations reveal information about the coherence and the quantum statistics of light [1]. This principle has found application in many fields of physics, such as astronomy, high-energy physics, atomic physics and condensed matter physics. It was theoretically predicted that a laser should be characterized by reduced intensity fluctuations compared to any thermal light source, no matter how narrow-band or intense.

For an explanation, it is instructive to look at the particle properties of light: photons from a thermal source bunch. In other words, if a beam is analyzed with a single-photon detector, and the detector just clicked, the detection of the next photon will most likely be directly thereafter. In a laser beam, however, the probability for a second photon detection in a beam of a given power is independent of the time elapsed since detection of the first photon. In an extremely elegant way, the stream of photons shows the lowest possible fluctuations because, if the photons were emitted one after the other like a stream of tennis balls thrown by one of these machines used in training, there would be times when the probability to detect the next ball is zero, namely directly following a given ball. This would be more regular, but at the same time less homogeneous.

Can such a tennis-ball-like stream of photons be created? Of course! The phenomenon is called antibunching and can be observed in resonance fluorescence of single atoms. Kimble already excited sodium atoms with a laser in 1977 and observed antibunching of the emitted photons [2]. The phenomenon is easily understood intuitively, as a single atom has to be re-excited after emission of a photon before it can emit another one. There is a general principle here: take one quantum system that you have decent control over; here atoms to tailor the properties of another quantum system; here a stream of photons. If there is only one very short excitation pulse, you will get at most one photon and have created a single-photon source.

Lasers cool atoms

So if there is a general principle, which quantum objects can be controlled with laser light (**Fig. 1**)? Lasers are used to cool and trap atoms, the prototypical particles.

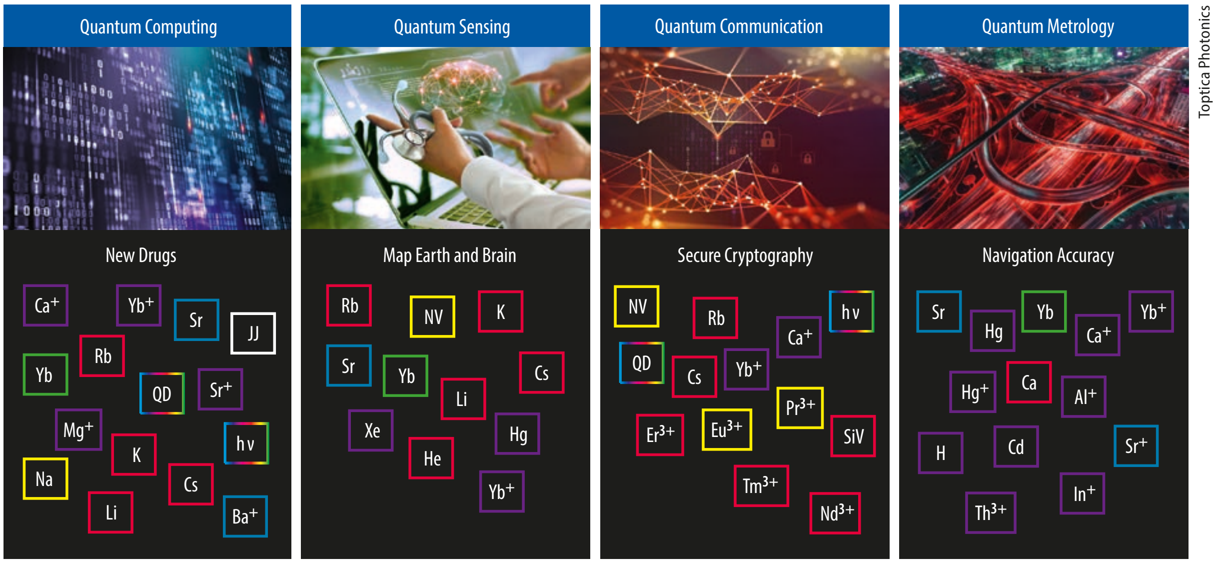

Fig. 1 Four pillars of quantum technologies (top) and a potential application result (below each image). There is a great variety of quantum systems used to implement different applications of quantum technologies. Species of atoms, ions and other quantum systems are shown in the square boxes. The more commonly used elements are at the top, the more exotic ones at the bottom.

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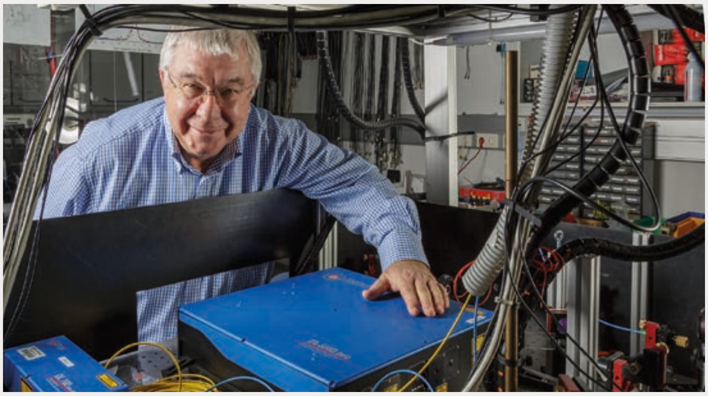

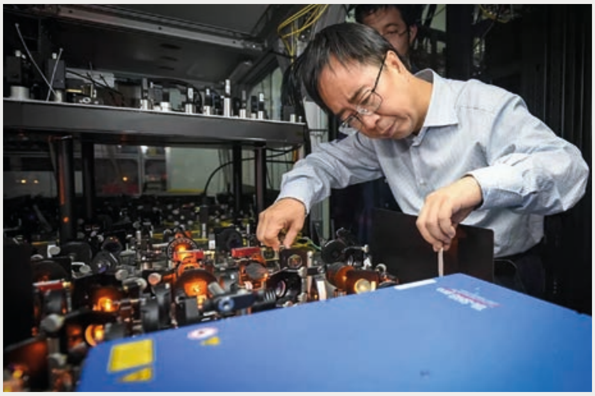

U. of Science and Technology of China, J.-W. Pan

The momentum of the photon is used to slow the atoms down. This research was awarded with the Nobel Prize in Physics in 1997, but it was just the beginning of the quest for the wave character of atoms. Only four years later, the Nobel Prize went to another trio of laser coolers and trappers. They had cooled an ensemble of atoms to the absolute ground state of motion, thereby creating a Bose-Einstein condensate. And suddenly the wave character of the atoms dominated their behavior. A source of atoms identical in all quantum states was available.

But we had that before, right? A coherent beam of particles with wave properties? The laser. So if one takes a beam of atoms from a Bose-Einstein condensate, one has an atom laser! Atom lasers can interfere, just like optical laser beams. But what about the minimal intensity fluctuations and the lack of bunching that was observed in laser beams? Of course, scientists performed these experiments and found bunching in a thermal beam of atoms [3] and the lack thereof in an atom laser [4]. In this respect there are no differences between optical and atom lasers. In the experiments with atoms, the laser light had turned from an object of investigation to a tool for the study of the quantum properties of atoms.

Another central phenomenon for two single, identical photons is their behavior on a beamsplitter. As Hong, Ou and Mandel showed in 1987, if two photons impinge on a 50 : 50 beamsplitter, one on each input port, they will always leave the beamsplitter together in one of the two output ports [5]: at which of it is random. Fast forward about two decades – and this effect of interference of probability amplitudes of photons at a beam splitter is the basis of quantum computation with linear optics and detectors [6]. In 2002 Jonathan Dowling and Gerard Milburn said: “The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies.” [7]

The quantum systems toolbox

The quantum systems at hand for quantum technologies are manifold (**Fig. 1**). There are atomic quantum systems, like optically and magnetically trapped atoms or trapped ions. Single photons and coherent states of light were mentioned before. Electron spins in quantum dots, vacancy centers in diamond and rare-earth ions in crystals are quantum systems in solid-state materials. The list is by no means complete, and new quantum systems continuously emerge. Laser systems represent an important tool to control these quantum systems. Diode lasers and tapered amplifiers are particularly energy efficient and available over a large range of wavelengths. Current trends are more power and automation for 24/7 hands-off operation and remote control of all relevant parameters. Beyond lasers, the quantum systems toolbox is extremely diverse and includes ultralow-noise stabilization, high-finesse cavities, optical frequency combs and wavelength converters (**Fig. 2**).

Quantum random numbers

One of the peculiarities of quantum mechanics is the measurement process. Measurement of a quantum system will project it into an eigenstate of the measurement basis. If the initial state was not one of these eigenstates, the measurement alters the state of the quantum system. A photon with circular polarization, sent onto a polarizing beamsplitter, will leave it with linear polarization. But whether it will be transmitted with horizontal polarization or reflected with vertical polarization is random. In fact, given perfect conditions, there is no process that could be more random. This property of quantum systems is put to good use in quantum random number generators. They are arguably the first application of quantum technologies in a mass market, as they found their way into a smartphone.

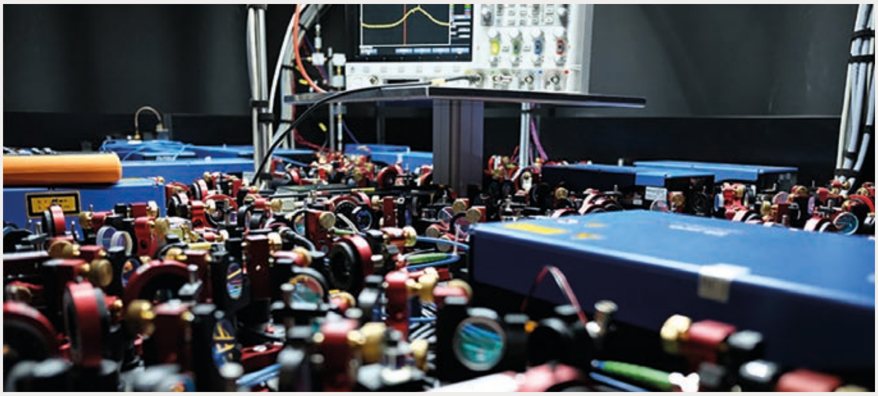
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Fig. 2 Examples of optics tables in modern quantum technology experiments. Rainer Blatt puts his hand on one of the laser systems in his lab at the University of Innsbruck, Austria (far left). Jian-Wei Pan aligns laser optics (center); and parts of the laser system in the research group of Ulrich Schneider, Cavendish Laboratory, University of Cambridge.

Quantum cryptography

There is another application targeting a very old problem that is more relevant than ever: cryptography. Imagine two parties exchanging quantum states. If an eavesdropper wants to learn anything about a quantum state, at least a partial measurement is indispensable. This will alter the state as long as the eigenbasis is unknown. Sender and receiver can therefore detect this interception if they compare the states that have been sent and received. Obviously, they cannot prevent the eavesdropper from interfering with their communication.

But it is possible to ensure that the eavesdropper does not learn anything useful in the interception if they restrict their communication to attempting to establish a secret key. As they can determine the maximum amount of information the eavesdropper can have gained about the key, they can use classical methods of privacy amplification to reduce the amount of information the eavesdropper will have about the final key to almost zero.

While quantum key distribution does not provide a means for authentication, its conceptual security is based on fundamental laws of physics. Practically, this happens via the exchange of photons. They can be transmitted through an optical fiber, through the atmosphere, or even between a ground station and a satellite in space, with each of these transmission paths having its own optimal wavelength. Quantum networks for the purpose of quantum key distribution will typically not be restricted to two network nodes and might be a heterogeneous combination of the different transmission paths. Technological prerequisites are a quantum channel that does not alter the quantum state too much, a sender producing single photons or weak coherent pulses of light in well-defined quantum states, and a receiver that can resolve, i.e. measure, these states.

The polarization is by no means the only physical property of a photon that can be employed for quantum key distribution. Researchers have shown that the photon's emission time (time bin qubit), its wavelength (frequency qubit) and its orbital angular momentum can be employed as well. Even mixed realizations are possible because these encodings of a quantum bit can be converted into each other.

Quantum networks

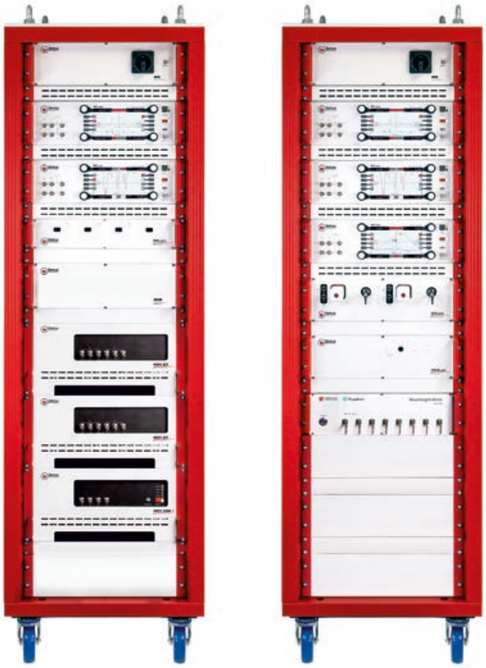
Establishing a quantum link between two quantum computers is another application. This is much more powerful than linking classical computers because the state space that quantum computers can explore scales exponentially with the number of qubits. An obvious quantum-link protocol maps the state of one of the qubits in quantum computer A onto a photon and sends the latter over to quantum computer B, where it is mapped back onto one of the qubits of the computer. But the attenuation of the photon in an optical fiber and related problems in free-space communication will put a limit on how far the two computers can be apart. For large distances, the photon will just not make it to the other end. Amplification of the photon, as in optical repeaters in classical optical communication, is not an option, because the amplification process will alter the state of the photon. This is a consequence of the no-cloning theorem of quantum mechanics and makes quantum key distribution tap-proof.

Quantum repeaters

The solution are quantum repeaters. While the first experimental demonstration of a scalable quantum repeater link is still outstanding, the task is much more tractable than the fully error-corrected scheme. It boils down to the distribution of entanglement between parties in the network that are close enough to allow for direct transmission. Entanglement is a non-classical and therefore non-trivial correlation between the states of two or more quantum systems. A concatenation of such entangled links can be used to achieve entanglement between the two outmost stations. There are theoretical concepts of how two parallel links of entangled quantum systems can be turned into a single one with higher entanglement fidelity.

Quantum teleportation

If you have entanglement between two quantum systems in remote locations, you can exchange any quantum state between them without physically transferring it. So there is a proven alternative to encoding the quantum state in a photon or any other physical object and transferring that object from one to the other location. This quantum teleportation requires entanglement and classical communication between the two locations plus the ability to perform suitable local quantum state measurements. Quantum teleportation enables lossless transfer of qubits, quantum logic gates between qubits in two remote locations, and quantum key distribution. Basically, remote entanglement is a resource for quantum information processing between remote locations. A quantum network that allows for entanglement between any of its network nodes is often called a quantum internet [8].



Toptica Photonics

Fig. 3 Laser rack systems are essential to bring quantum technologies out of the lab and into applications. Because the required laser systems are as diverse as the quantum technologies themselves, Toptica provides a modular toolbox of laser systems with maximum wavelength coverage, control electronics and frequency references. The system shown can be used to build a strontium optical lattice clock.

Wealthy quantum technologies

The above examples illustrate how an understanding of the physics of quantum systems has led to intriguing quantum protocols. In combination with experimental mastery of quantum systems, they can be turned into applications. It is a natural consequence of the importance of photonics for quantum technologies that a laser company like Toptica Photonics is a partner in four different European Quantum Flagship Projects.

In the European Quantum Flagship Project Quantum Internet Alliance (QIA), Toptica is one of the partners that is working towards a quantum internet. Besides, Toptica solves technological challenges for quantum simulation in the PASQuanS project, and develops and provides laser systems tailored for gate-based quantum computing (Quantum Flagship project AQTION) and for optical clocks (Quantum Flagship project iqClock). In all four projects, laser systems with extreme specifications are the tools that allow for the preparation, manipulation and readout of matter-based quantum systems with surgical precision (**Fig. 3**). Over the last decades, we have applied our understanding of the underlying physics and have gained sufficient technological control of quantum systems to turn them into practical tools. This is quantum technology 2.0!

The power of quantum technologies is based on three pillars: first, fundamental research, where the properties of quantum systems were discovered; second, clever people conceived protocols, turning these properties into applications; and third, groundbreaking technological achievements constantly shift the boundary between what can only be imagined and what can actually be implemented. I believe that the short-term expectations placed on quantum technologies disregard many of the technological and conceptual challenges that lie ahead. But I am convinced that we have only started to understand what quantum technologies hold in store for us. The fascination for the subject is well-grounded. The open questions are which quantum technologies will make a difference to our everyday life – and when. I could not be more curious to find out.

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