Diamond-based light sources will lay a foundation for quantum communications of the future

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Dmitry Fedyanin from the Moscow Institute of Physics and Technology and Mario Agio from the University of Siegen and LENS have predicted that artificial defects in the crystal lattice of diamond can be turned into ultrabright and extremely efficient electrically driven quantum emitters. Their work, published in *New Journal of Physics*, demonstrates the potential for a number of technological breakthroughs, including the development of quantum computers and secure communication lines that operate at room temperature.

The research conducted by Dmitry Fedyanin and Mario Agio is focused on the development of electrically driven single-photon sources—devices that emit single photons when an electrical current is applied. In other words, using such devices, one can generate a photon "on demand" by simply applying a small voltage across the devices. The probability of an output of zero photons is vanishingly low and generation of two or more photons simultaneously is fundamentally impossible.

Until recently, it was thought that quantum dots (nanoscale semiconductor particles) are the most promising candidates for true single-photon sources. However, they operate only at very low temperatures, which is their main drawback – mass application would not be possible if a device has to be cooled with liquid nitrogen or even colder liquid helium, or using refrigeration units, which are even more expensive and power-hungry. At the same time, certain point defects in the crystal lattice of diamond, which occur when foreign atoms (such as silicon or nitrogen) enter the diamond accidentally or through targeted implantation, can efficiently emit single photons at room temperature. However, this has only been achieved by optical excitation of these defects using external high-power lasers. This method is ideal for research in scientific laboratories, but it is very inefficient in practical devices. Experiments with electrical excitation, on the other hand, did not yield the best results – in terms of brightness, diamond sources lost out significantly (by several orders of magnitude) to quantum dots. As there were no theories describing the photon emission from colour centres in diamonds under electrical excitation, it was not possible to assess the potential of these single-photon sources to see if they could be used as a basis for the quantum devices of the future.

The new publication gives an affirmative answer – defects in the structure of diamond at the atomic level can be used to design highly efficient single-photon sources that are even more promising than their counterparts based on quantum dots.

Operation at the single-photon level will not only increase the energy efficiency of the existing data processing and data transmission devices by more than one thousand times, but will also lay the foundations for the development of novel quantum devices. Building quantum computers is still a prospect of the future, but secure communication lines based on quantum cryptography are already in use. However, these are not true single-photon sources; instead, they rely on what are known as attenuated lasers. This means that not only is there a high probability of sending zero photons into a channel, which greatly reduces the speed of data transfer, but there is also a high probability of sending two, three, four, or more light quanta simultaneously. One could intercept these "extra" photons and neither the sender nor the recipient would be aware. This makes the communication channel vulnerable to eavesdropping and quantum cryptography loses its main advantage – fundamental security against all types of attacks.

Quantum computing it requires the ability to manipulate individual photons. The quantum of light can be used to represent a qubit – the fundamental unit of quantum information processing – which is a superposition of two or more quantum states. For example, a qubit can be encoded in the polarization of a single photon. The advantage of the optical quantum computing paradigm is that one can natively combine quantum computations with quantum communication and design high-performance, scalable quantum supercomputers, which is not possible using other physical systems such as superconducting circuits or trapped ions.

Dmitry Fedyanin and Mario Agio are the first to successfully reveal the mechanism of electroluminescence of colour centres in diamond and develop a theoretical framework to quantify it. They found that not all states of colour centres can be excited electrically, despite the fact that they may be "accessible" under optical excitation. This is because under optical pumping, defects behave like isolated atoms or molecules (such as hydrogen or helium) with virtually no interaction with the diamond crystal.

Electrical excitation, on the other hand, is based on the exchange of electrons between the defect and the diamond crystal. This not only brings limitations, but also opens up new possibilities. For example, according to the researchers, certain defects can serially emit two photons at two different wavelengths from two different charge states in a single act of the electroluminescence process. This feature could lead to the development of a fundamentally new class of quantum devices that had simply been disregarded before because these processes are not possible with optical excitation of colour centers. But the most important result of the study is that the researchers found out why high-intensity, single-photon emission from colour centers was not observed under electrical pumping. This is due the technologically complex process of doping diamond with phosphorus, which cannot provide sufficiently high density of conduction electrons in diamond.

The calculations show that using modern doping technologies it is possible to create a bright single-photon source with an emission rate of more than 100,000 photons per second at room temperature. It is truly remarkable that the emission rate only increases as the device temperature increases, achieving more than 100 million photons per second at 200 degrees Celsius. "Our single-photon source is one of few, if not the only optoelectronic device that should be heated in order to improve its performance, and the effect of improvement is as high as three orders of magnitude. Normally, both electronic and optical devices need to be cooled by attaching heat sinks with fans, or by placing them in liquid nitrogen," says Dmitry Fedyanin from the Laboratory of Nanooptics and Plasmonics at MIPT. According to him, the technological improvement of diamond doping will further increase the brightness 10 to 100 times.

One hundred million photons is very low compared to household light sources (a normal light bulb emits more than 10^{18} photons per second), but the entire flow of photons is created by a tiny (~10^{-10} metres) defect in the crystal lattice of diamond. And unlike a light bulb, photons follow strictly one after the other. For the quantum computers mentioned above, around 10,000 photons per second would be enough – the possibility of developing a quantum computer is currently limited by entirely different factors. In quantum communication lines, however, the use of electrically driven diamond single-photon sources will not only guarantee complete security, but will also greatly increase the speed of information transfer compared to the pseudo single-photon sources based on attenuated lasers used today.

More information: D.Yu. Fedyanin, M. Agio, *Ultrabright single-photon source on diamond with electrical pumping at room and high temperatures* // New Journal of Physics 18, 073012 (2016).

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