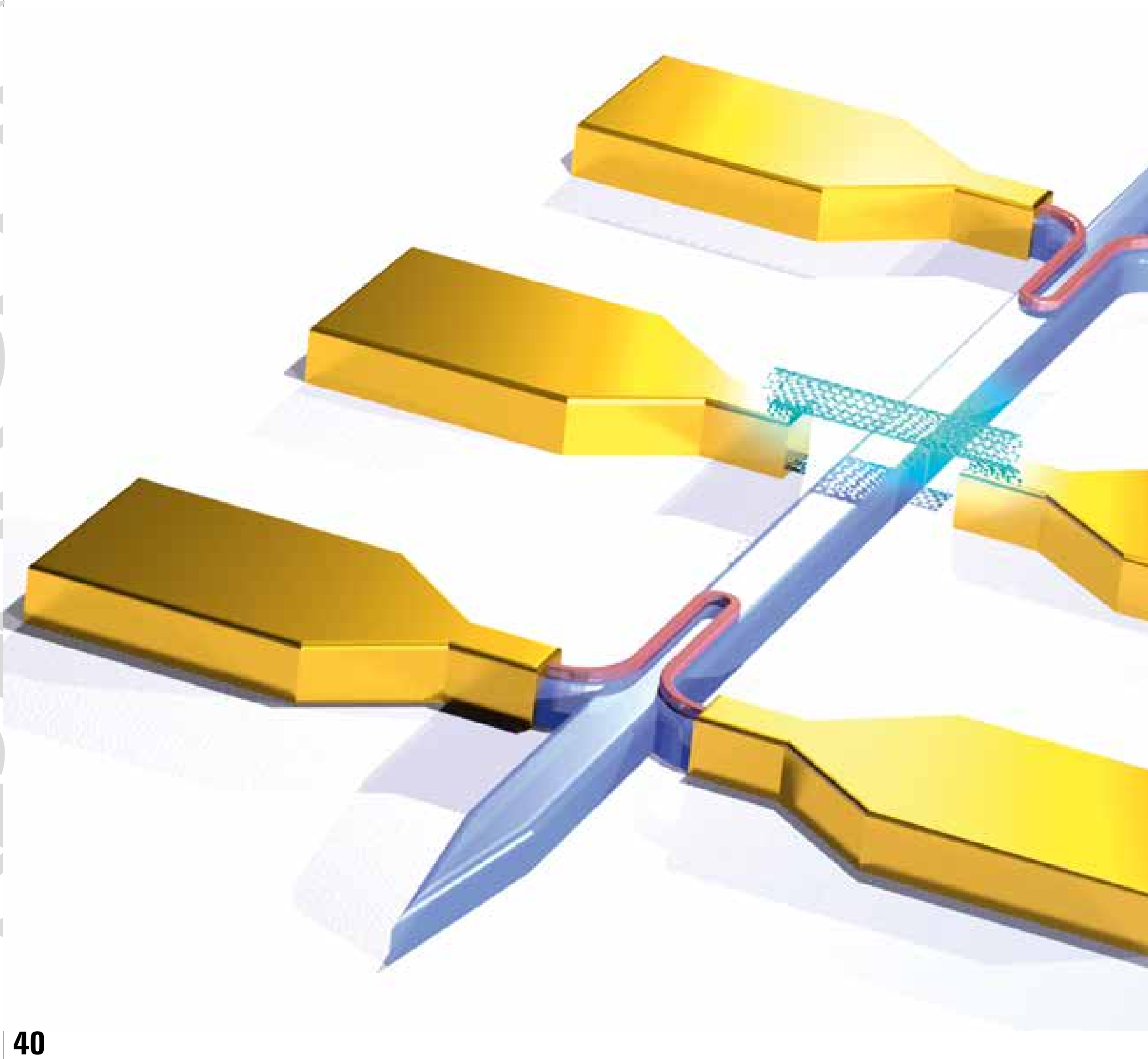
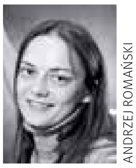
Tiny yet Powerful: Carbon Tubes for Quantum Light



“Soon we will be able to fit the contents of the *Encyclopedia Britannica* on a head of a pin,” the famous physicist Richard Feynman argued back in the 1960s. Perhaps even he would be amazed at the possibilities now offered by carbon nanotubes, several hundred thousand times tinier than a pin. Their amazing properties have been exploited in an integrated circuit developed at the Karlsruhe Institut für Technologie.

Dr. Karolina Słowik

Nicolaus Copernicus University in Toruń



ANDRZEJ ROMAŃSKI

Dr. Karolina Słowik
is an Assistant Professor at the Institute of Physics at the Nicolaus Copernicus University in Toruń. She is a laureate of the National Science Centre POLONEZ 1 competition, and recipient of the HOMING grant funded by the Foundation for Polish Science (FPS). Since 2016 with her team she has been working on the HEIMaT research project funded by FPS, which studies the impact of plasmonic nanostructures on quantum transitions in molecules.

karolina@fizyka.umk.pl

The first digital computers, developed in the 1940s and 1950s, brought within our reach problems previously inaccessible. From military applications, through modelling of physicochemical or biological systems, to macroeconomic problems: all these issues required calculations too complicated to be performed with a pencil and a piece of paper or an abacus. Today we stand at the dawn of a new era of quantum computers: devices holding the promise of new technologies millions of times more powerful than those currently available. But to take full advantage of their enormous potential, we must first solve the scalability problem and learn how to build quantum circuits capable of processing enough quantum bits.

The age of the Q-bit

Operations performed by computers rely on the processing of series of zeros and ones, in which information is encoded in the form of either a presence or an absence of electric current. Quantum bits, known as Q-bits, have much greater capacity: the laws of

Fig. 1
Diagram of a photonic integrated circuit: a centrally located graphene nanotube rests on the gold electrodes supplying the voltage. The electrically stimulated nanotube emits photons, which propagate along the perpendicularly positioned optical fibers. Detection occurs in the super-cooled superconducting wires, which once slightly heated by photon absorption no longer conduct current between the gold connectors.

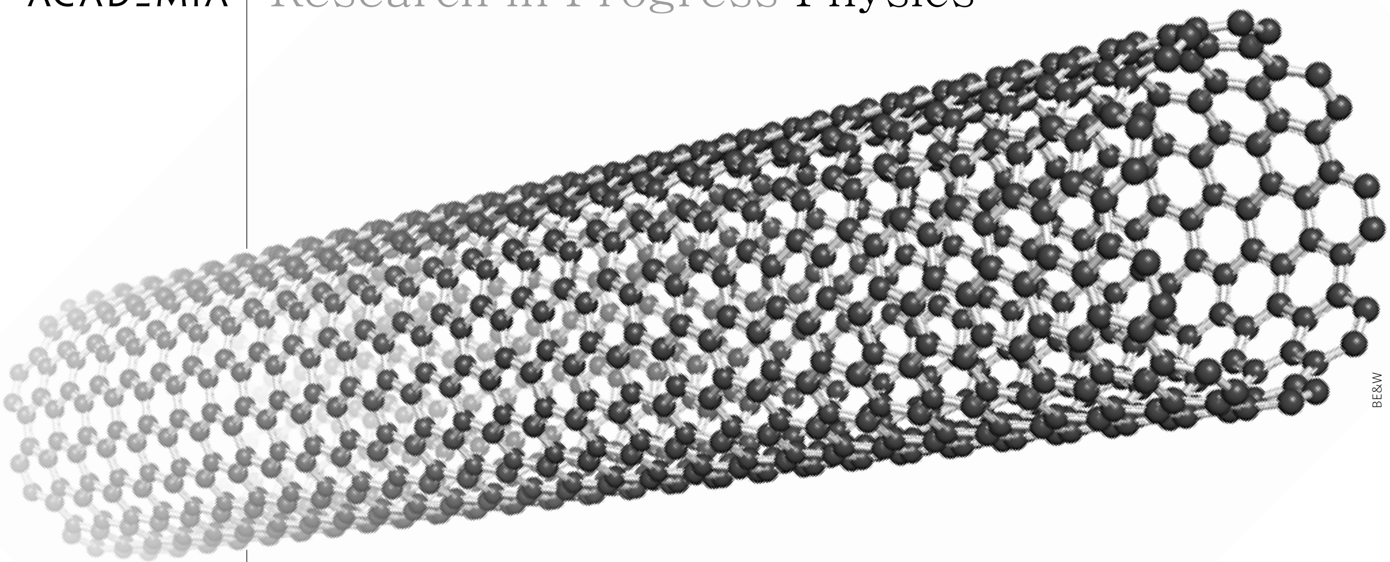


Fig. 2
A graphene nanotube, formed by rolling a network of honeycomb-shaped carbon atoms. The diameter of the tube illustrated is about 2.5 nm, which is one four hundred thousandth of a millimeter.

quantum physics allow them to encode both the values of 0 and 1 simultaneously (the superposition principle). It is the ability to perform simultaneous operations on all possible data values that is at the heart of the anticipated enormous power of quantum computers.

It is estimated that a machine capable of simultaneously processing 50 Q-bits will render today's most powerful supercomputers obsolete. This would enable efficient modelling of various kinds of processes: biological (including developing new drugs through simulations of their interactions with proteins), chemical (such as obtaining very accurate information on the energy of molecular bonds), meteorological (including climate change modelling), and intermolecular (which may aid in developing new, much stronger and more flexible materials). It would also facilitate efficient analysis of large information sets, including sociological and astronomical data, using machine learning techniques, whereby computers search databases to identify patterns of which we might not even be aware.

It is not surprising then that companies such as Google, IBM, Microsoft and D-Wave are already implementing quantum technology prototypes. IBM has created a multi-byte machine accessible on the Internet, where users can run their own quantum algorithms. At this time, however, we have yet to develop a truly scalable technology solution, allowing calculations to be performed on a large number of Q-bits.

The Minirecord

One of the possible ways that a Q-bit might actually be implemented involves polarization of a single photon: an indivisible particle of electromagnetic radiation, the weakest possible signal that can exist. The performance of photon-based quantum algorithms has been confirmed in laboratories numerous times. Usually, however, these experiments are carried out on huge optical tables, which is not feasible on an industrial scale. The construction of a quantum processor will require tiny sources and detectors, which would allow photons to be efficiently emitted and afterwards detected. Trends in the field have therefore accelerated towards constructing integrated circuits for light, combining these elements on tiny chips. Miniaturization brings additional benefits. Small size means short time scales of conducted operations, thus facilitating the coordination of a large number of Q-bits.

So far, the smallest of such integrated circuits was developed at the Karlsruhe Institut für Technologie, in a collaborative project involving scientists from Germany, Russia, and Poland, led by Professor Wolfram Pernice. It consists of three components: carbon nanotubes as light sources, a waveguide, which allows the propagation path of photons to be controlled, and a pair of extremely sensitive detectors to detect signals as weak as individual particles of light. An additional advantage of the circuit is that it is electrically driven, as opposed to the laser excitation method usually applied in laboratories. Thus there is no need to filter the strong laser beam from the weak quantum signal. The entire chip measures just a fraction of a millimeter. The technology allows for the production of dozens of such devices in one cycle.

Carbon "stars"

In the circuit, nanotubes play the key role of photon sources. Such tubes are made exclusively of carbon, an element found on our planet in high abundance, which translates into relatively low production costs. Their attractiveness from the technological point of view lies in the fact that they can be relatively easily integrated into existing production methods of integrated circuits, a fact that was crucial for the experiment at Karlsruhe.

Nanotubes are formed by rolling graphene (a single layer of graphite, the material found inside a pencil) into a tube. As the name suggests, they are very small, having a diameter of about one nanometer, which is one hundred thousand times smaller than the diameter of a single strand of human hair. Graphene is not an isotropic material, which means that its properties, such as its strength or electrical conductivity, depend on the direction along which the graphene plane is rolled in. With this direction, the optical properties of nanotubes also change, including the color of light that they emit. The rapid development of nanotechnology over the last decade and a half has resulted in the emergence of techniques not only for the production of nanotubes on a large scale, but also for sorting them depending on their geometry. This means that we can select those carbon nanotubes that emit visible light in a desired color or radiation in a predetermined range of the infrared domain.

In the Karlsruhe experiment, selected types of nanotubes were carefully placed on gold electrodes previously mounted on a glass chip base. Electrodes delivered voltage to the nanotubes, resulting in current flow. In the graphene, electric energy provided in this way underwent a very efficient conversion into radiation in a process called electroluminescence. The emitted photons were captured by dielectric optical fibers, which guided them straight to the detectors. Their signal confirmed the act of emission and detection of light.

Creating detectors sensitive to signals as weak as only one photon is in itself a technological achievement. Many such devices already exist and are used in research laboratories. In the experiment, however, the performance requirements for the detectors were particularly high, because the process of electroluminescence occurs in nanotubes very quickly. The time required for conversion of electricity to light was less than one hundred picoseconds, or less than one ten billionth of a second. This means that the detector needed to have a particularly high resolution time, which was achieved through the use of superconductivity in conjunction with a very precise engineering of the optical fiber geometry.

Superconductivity is a phenomenon in which current can flow through wires with virtually no resistance. This phenomenon requires ultra low temperatures and stops abruptly when the wire is heated by a fraction of one degree Celsius. The operation of superconductive detectors therefore requires the system to be cooled with liquid helium down to a temperature of 1.6 K or about -271.50C. Even the temperature out in cold interstellar space is higher than that. While the detector is operating, the superconducting current flows through this extremely cooled wire. When a photon comes close, its energy is absorbed, which heats the wire and immediately cuts off the current flow. This is how the presence of a photon is detected. A relatively long wire is needed in order for the detection process to be effective as this increases the probability of interaction with a photon. However, this prolongs the time it takes for a single act of detection, and therefore reduces the resolution time of the device.

Double connection

The Karlsruhe team together with colleagues from the Moscow State Pedagogical University has therefore developed technology in which the superconducting wire crosses the path of the photon at right angles. This might have reduced the likelihood of detection due to the shortened photon interaction. To prevent it, rows of carefully sized holes were drilled in the optical fibers on both sides of the superconducting wire. Surprisingly, such holes act just like a mirror: the back of the wire fully reflected the photons, whereas the front of the mirror was semitransparent so as to allow the photons to enter, but not to exit. This allowed for an almost ideal absorption, in conjunction with high resolution time of detection, enabling a substantial portion of the light emitted by the nanotubes to be detected.

The aim of the experiment was not only to show that nanotubes can be used as sources of radiation, but above all to prove that single photons rather than bunches thereof are most often produced in the emission process. This is crucial for quantum computing, as well as for quantum communication and other quantum optic applications. This is why the nanotube was connected through an optical fiber to not one, but to two detectors. Each photon emitted, due to its indivisible nature, could be observed by only a single detector, inducing a signal within it, called a click. Had the pulses generated by the nanotubes been composed of a larger number of photons, each of them would individually propagate along one of the two optical fibers. This would occasionally lead to simultaneous clicks by both detectors, called coincidence. Statistical analysis of the number of coincidences relative to the total number of clicks allowed us to confirm that the emission in the experiment was largely of a single-photon nature.

The experiment marks a milestone on the path to the construction of optical quantum computers. Many technological problems have been solved on the way and certain established ways of thinking have been reviewed. This has helped develop scalable technology to produce the smallest, electrically powered photonic integrated circuits, based on readily available, high-speed sources and cutting-edge solutions in the field of detection. Prospects for further development include narrowing the range of colors of the emitted light, enriching chips with additional optical elements, and performing interference experiments with increasing numbers of Q-bits encoded in the photons generated. Most likely, this road will also be full of challenges, but overcoming them will lead us straight into the era of quantum technology.

Karolina Słowik

Further reading:

Khasminskaya S., Pyatkov F., Słowik K., Ferrari S., Kahl O., Kovalyuk V., Rath P., Vetter A., Hennrich F., Kappes M. M., Goltsman G., Korneev A., Rockstuhl C., Krupke R., Pernice W. H. P. (2016). Fully integrated quantum photonic circuit with an electrically driven light source. *Nature Photonics 10 (11)*, 727–732.

Pyatkov F., Fütterling V., Khasminskaya S., Flavel B.S., Hennrich F., Kappes M. M. Krupke R., Pernice W. H. P. (2016). Cavity-enhanced light emission from electrically driven carbon nanotubes. *Nature Photonics 10 (6)*, 420–427.

Vetter A., Ferrari S., Rath P., Alaee R., Kahl O., Kovalyuk V., Diewald S., Goltsman G. N. Korneev, A., Rockstuhl C., Pernice W. H. P. (2016). *Cavity enhanced and ultrafast superconducting single-photon detectors*. Nano Letters.