optics & photonics focus

What a Molecular Transistor!

How far can a single, tiny molecule go? Exceeding most people's imagination, researchers have shown that a single molecule can actually work as a transistor for photons.

What is the major technological breakthrough of the 20th century? According to the U.S. National Academy of Engineering's top 20 list [1], electronics, computers, lasers and optical communications are all good candidates. Which is the common denominator amongst them all? The transistor, of course; invented in 1925, the transistor heralded a new era in technology. Our world would not be the same without it. Vahid Sandoghdar and his Nano-optics group of researchers at the Swiss Federal Institute of Technology (ETH) in Zurich have now shown that a single molecule can actually perform on photons all the operations that a standard transistor can perform on electrons — a huge step forward towards all-optical computation.

Where does the advantage of using photons instead of electrons lie? Light is fast, faster than anything else. Light is already the standard tool for telecommunications: optical fibers have been steadily substituting old copper cables with overwhelming advantages in terms of performance. Nonetheless, computation is still mainly performed by electrons in electronic devices. The use of photons instead could speed things up, and cutting-edge research is already exploring various optical alternatives to electronics, including those based on metamaterials [2] or excitons [3-4].

The transistor is the fundamental building block of almost all electronic equipment today. Transistors are used to control the flow of electrons in electrical signals. A low-intensity electrical power is able to make the transistor function as a gate that controls another incoming electrical signal of greater intensity, in the same way that a valve controls water flow from a tap. When the first signal reaches a certain threshold, the gate opens and lets the incoming electrical flow from the larger power supply go through. Below that threshold, the gate closes. The job of the transistor is, therefore, to amplify or attenuate an incoming electrical signal depending on a controlling, lower-intensity current. Another way of seeing transistors is as a binary switch: for example, an open gate can be encoded as a digital 1 and a closed gate as a digital 0. Transistors are a key component in electronic devices such as computers because they can be arranged into networks and perform all kinds of binary operations.

Nonetheless, "these basic operations... when performed with electrons, present limitations, such as losses, heating, and cross-talks between electrons. It would be interesting if the same operations could be performed using light," says Sandoghdar. The main advantage of light is that it is faster than anything else, and using photons instead of electrons could greatly speed things up. "This opens new difficulties, though. Controlling light by using light is not possible, since photons do not interact between themselves."

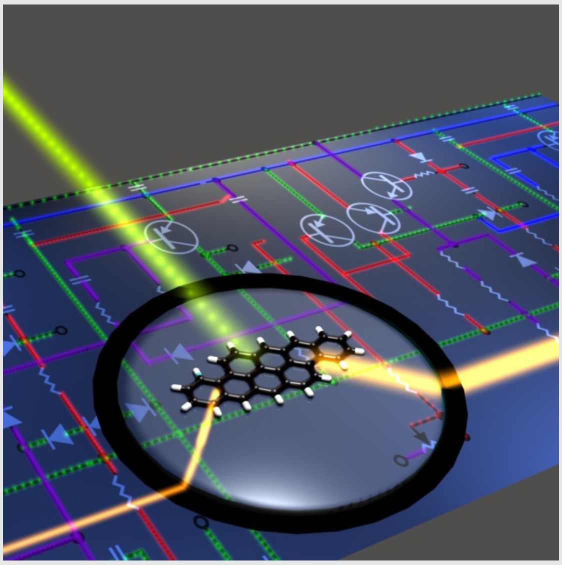

Figure 1: A molecular integrated circuit. An artistic representation of a fully optical circuit created on building bocks such as the single molecule optical transistor. In the black circle, a molecule is amplifying a light signal (yellow), exactly as a transistor does on electronic signals. The control over the amplification is given by a second light beam (green), which decides whatever the molecule is amplifying, attenuating or leaving the input signal unaltered.

Sandoghdar and his team at ETH have overcome this challenge by using single molecules to mediate interactions between photons. Molecules can thus emit light in a process called stimulated emission: when bombarded with photons of the correct energy, electrons within a molecule can reach an excitation state and then come back to normal by releasing new, identical photons. However, "stimulated emission in molecules is usually an inefficient process... By going to low temperature in order to increase the molecular cross-section and by focusing light to diffraction limit, we achieved the higher efficiency needed to perform our experiment," Sandoghdar says.

What is "an appropriate medium"? Molecules can emit light through a process called stimulated emission — the same working principle of lasers: an electron, after being perturbed by a photon with the proper energy, emits a second photon with the same phase, frequency, polarization, and direction of travel as the original. However, obtaining stimulated emission from a molecule with good efficiency, "is tricky from the experimental point of view," Sandoghdar points out. "In fact, stimulated emission in molecules is usually an inefficient process, because light is not strongly focused and single molecules do not have a broad cross-section. By going to low temperature in order to increase the molecular cross-section and by focusing light to diffraction limit, we achieved the higher efficiency needed to perform our experiment."

In order to show the single molecule optical transistor at work, two laser sources are needed. The first laser pumps the electrons of the molecule in an appropriate energy state; a second laser sources then stimulates the secondary emission of photons from the molecule. In these terms, the first laser works like the control current in a transistor. It can. therefore, decide when to open or to close the molecular gate, i.e. when the molecule only absorbs the photons of the second laser or when it emits more by stimulated emission. "Three actions are, therefore, possible on the second beam, i.e. to attenuate it up to ten percent, leave it unaltered or amplify it up to one percent." Even though this efficiency might sound very low, Diederik S. Wiersma, leading the group of Optics of Complex Systems at LENS (European Laboratory for Non-linear Spectroscopy in Florence, Italy), explains that "you need to compare this result to other non-linear effects where usually not more then one photon out of a million is affected. The efficiency achieved in this work is incredibly high since you can control nearly all the photons of a light beam this way."

The ETH researchers think there is a long way to go before identifying any practical applications for their findings. For example, "it is not clear to me," Sandoghdar admits, "how wiring at the nanoscale could be achieved in order to make such optical transistors communicate between them. The low temperature, fundamental in our experiment, is another issue for real applications and, moreover, a higher efficiency will be needed; maybe atoms will work better than what molecules do. Right now, academic applications are for sure easier to tackle for this system, such as, for example, exploring quantum information schemes. It is amazing though," he adds "to see what a small element, like a single molecule, can do in terms of light absorption and amplification."

As this work shows, there is still a lot to do in these days in nanophotonics before electronics will be substituted by all-optical circuits, but, as Wiersma says, "this result is a really important step forward. It might be that, one day, we could use these single-molecule optical transistors as building blocks for creating fully optical circuits, which, of course, would be fantastic." When the first electronic transistor was developed it was huge and it seemed impossible that a centimeter size object would ever be scaled down and become as useful as it is today. The same holds for the first laser which filled an entire room and was considered completely useless in the early days. What followed is history: transistors are the heart of modern electronics, and lasers are used for surgery, CD players, bar code scanners, and much more. "Application driven research," Wiersma concludes, "will never provide real scientific progress and, vice versa, it is impossible to know all the applications that can come out of an important scientific result. Do not forget, therefore, to look also at the shear beauty of the result as such: these researchers managed to block and control a beam of light with one single molecule, which is a really exceptional achievement!"

[1] G. Constable and B. Somerville, *A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives*, Joseph Henry Press (2003).

[2] N. Engheta, *Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials*, Science **317**, 1698 (2007).

[3] A. A. High *et al.*, *Exciton optoelectronic transistor*, Opt. Lett. **32**, 2466-2468 (2007).

[4] G. Volpe, *Will Excitonic Circuits Change our Lives?*, Opt. Photon. Focus **2**, 3 (2008), http://www.opfocus.org/index.php?topic=story&v=2&s=3.

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J. Hwang, M. Pototschnig, R. Lettow, G. Zumofen, A. Renn, S. Götzinger, and V. Sandoghdar, **A single-molecule optical transistor**, Nature (2009) **460**, 76-80.