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Viewpoint

User Friendly Photon Pairs

Gregor Weihs
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria

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Researchers have fabricated an electrically powered semiconductor device that creates photon pairs.

Subject Areas: **Quantum Information, Optoelectronics**

A Viewpoint on:
Electrically Injected Photon-Pair Source at Room Temperature
Fabien Boitier, Adeline Orieux, Claire Autebert, Aristide Lemaître, Elisabeth Galopin, Christophe Manquest, Carlo Sirtori, Ivan Favero, Giuseppe Leo, and Sara Ducci
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For many researchers, quantum entanglement has become merely a tool that is being put to use, or a resource that has to be accounted for. For others, like me, entanglement has not lost any of its fascination. Whether it is the fascination we want to explore or a tool that we would like to hone, most of us agree that it would be fantastic to have something like an entanglement laser pointer. Push a button on a small battery-powered device and out come your entangled photon pairs. A dream? Fabien Boitier at Paris Diderot University–Paris 7, France, and co-workers have just brought this dream much closer to reality. In *Physical Review Letters*[1] they write about how they realized an electrically powered semiconductor source of photon pairs. While they have not demonstrated entanglement yet, the data suggest research is moving in the right direction.

The traditional and, by many measures, still best sources of entanglement are based on spontaneous parametric down-conversion (SPDC). SPDC is the process that splits a blue photon into two red ones by means of a nonlinear optical crystal. It is thus just the inverse process of frequency doubling, which is used to convert laser light to higher frequencies—chances are that your green laser pointer uses this doubling process internally to convert infrared radiation to green. SPDC has been used in quantum optics for many years. It typically needs to be pumped by powerful blue lasers and requires many optical components fixed to a massive steel optical tabletop that provides stability. This is a far cry from the entanglement laser pointer we were hoping for.

Why is it so difficult? In SPDC, energy and momentum of the photons are conserved—nothing is exchanged with the crystal. Now while there is no problem with the energy conservation, conserving the momentum of the blue photon is often tricky. Red light is usually faster than blue, and thus the total momentum of the two red photons may not add up to the momentum of their blue parent. In this case, momentum cannot be conserved, and the process doesn't happen (or happens with an extremely small efficiency). Traditional sources [2] exploit the birefringence of the conversion crystal, which allows finding orientations and directions in which the initial and final momenta do match. Because the momentum of a photon is closely related to its spatial phase this is also called phase matching. Another way of thinking about this is to say that the velocities of the blue and red photons have to be the same. The velocity of light is dictated by the refractive index, and so, effectively we have to arrange for the refractive indices of red and blue to be identical: If the two colors do not march together, the process loses efficiency.

Boitier *et al.* use SPDC in their source, but in the semiconductor AlGaAs, which lacks any birefringence (see Fig. 1). In their scheme, the quantum-well laser emits a photon at 780 nanometers (nm) that is converted into a telecom-wavelength photon pair by SPDC. Many other ways of achieving phase matching in this material have been tried with limited success, but the recent development of Bragg-reflection waveguides (BRWs) [3] made from varying compositions of AlGaAs has been the breakthrough [4]. Instead of birefringence, waveguide modes with their effective refractive index make sure that the "red" and "blue" photons march in lockstep. In particular, the "blue" photon is guided by interference from the Bragg-reflection cladding layers of the waveguide and thus can assume a velocity that is quite different from its natural value in the host material. As a bonus, one can easily tune the phase matching to the desired region by slightly changing the waveguide dimensions and pick from a variety of polarization configurations for the three beams. This flexibility comes in handy when entanglement is the goal.

But why a semiconductor in the first place? AlGaAs is the material out of which many near-infrared lasers

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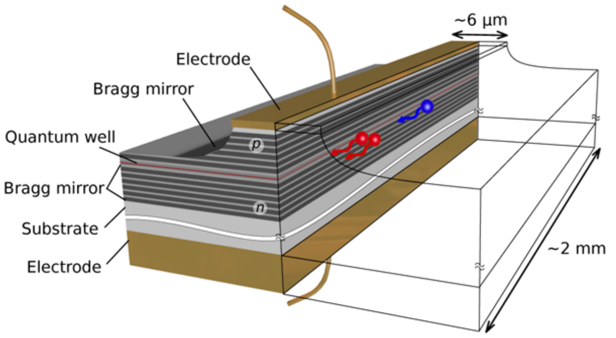

FIG. 1: Cutaway diagram of the combination laser/parametric down-converter developed by Boitier *et al.* to create entangled photon pairs. The "blue" laser photon, generated as in a regular diode laser, is converted to a pair of "red" photons. (Adapted from F. Boitier *et al.*[1])

are made. If we are looking for a platform that supports both the laser for producing the parent photons and the SPDC process, optical semiconductors are our materials of choice. Furthermore, AlGaAs has an extremely high nonlinearity, so if the phase matching can be tamed, one can expect very efficient devices. For communication applications, designers prefer producing photon pairs in the low-loss telecommunications band, around a wavelength of 1550 nm. Therefore our "blue" photons are in the near infrared, about 780 nm wavelength and the "red" photon pairs are in the infrared at twice the wavelength, i.e., 1560 nm.

While one might think that the problem is now solved by creating a standard laser diode and down-converter on the same chip, combining the two devices is actually difficult: They have different and, in part, contradictory requirements; for example, doping is necessary to get the electrical currents flowing into the structure, but doping also makes the waveguide lossier, because of the free charge carriers it generates. Building on earlier work [4, 5], Boitier *et al.* managed to strike a delicate balance between high nonlinear conversion efficiency, low optical losses, high laser gain, and sufficient electrical conductivity to finally produce a device that does it all.

The authors show lasing in the desired Bragg mode, temperature tuning (the wavelength is varied between 784 nm and 788 nm by changing the temperature over a 20 K range), frequency doubling, and finally the telltale sign that the device emits predominantly photon pairs, with only very little background: A time-to-digital converter, used to analyze the temporal correlations between detected photons, shows that photons come simultaneously in pairs (with a narrow coincidence counting peak). Given the calculated spectra, the researchers even go as far as estimating the expected polarization entanglement. Last year, our research group experimentally demonstrated that by separating the emitted photon pairs of an optically pumped BRW into a short and long wavelength beam by means of a dichroic beam splitter, one can generate polarization entanglement [6]. If you find a horizontally polarized photon in one beam, you are sure to find a vertically polarized one in the other and vice versa. If these two possibilities are coherent you have got yourself a polarization entangled state. If used in the same scheme, Boitier *et al.* calculate that their device would produce Bell states (i.e., entangled quantum states of two qubits) with a fidelity of about 90% (fidelity is one of the most commonly used metrics of quantum distances between states). This fidelity would allow tests of Bell inequalities—an important ingredient for any quantum scheme.

Because the goal of the entanglement laser pointer is so attractive, there are other approaches too. Our collaborators and we pursue an approach that aims to integrate whispering-gallery-mode lasers with the BRWs. This would afford more design flexibility and possibly lower threshold lasing but, on the other hand, poses bigger fabrication challenges. It is too early to tell which approach will turn out to be the best. But Boitier *et al.*'s result has certainly raised the bar and re-energized these efforts.

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About the Author

Gregor Weihs

Gregor Weihs is Professor of Photonics at the University of Innsbruck, Head of the Institute for Experimental Physics, and Adjunct Associate Professor at the University of Waterloo's Institute for Quantum Computing. He received his M.Sc. degree from Innsbruck University in 1994. His Ph.D. degree from Vienna University was awarded *sub auspiciis praesidentis* by the President of the Austrian Republic in 2000. Further positions included a junior faculty position at the University of Vienna and Consulting Assistant Professor at Stanford University. His major awards were the Canada Research Chair in Quantum Photonics and a Starting Grant by the European Research Council. In 2011, he was elected into the Austrian Academy of Sciences as a member of the Young Academy, and he is a Fellow in the QIS program of the Canadian Institute for Advanced Research. His research interests include fundamental physics, quantum and semiconductor optics, and quantum information.

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