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Quantum optics researchers force photons to behave like electrons

Based on theoretical considerations of physicists from Universität Greifswald, the Solid State Optics group of Professor Alexander Szameit at Universität Rostock achieved a major breakthrough: The realization of photonic topological insulators as conduits for light, in which photons behave like electrons and exhibit fermionic properties. Their discovery was recently published in the renowned journal "Nature Materials".

Electronic topological insulators – solids that do not conduct electricity in their bulk, yet are perfectly conductive along their surface – have been experimentally realized for the first time in 2007 by Laurens Molenkamp and his team at Universität Würzburg. In contrast, the question whether such a system may also exist light, was largely regarded as contradiction in terms. "Photonic topological insulators? Impossible!", Professor Alexander Szameit summarizes the prevalent opinion in his field. "As it turns out, this is mostly true," Szameit explains, "since photons are so-called bosons, and as such are fundamentally different from electrons, which are classified as fermions."

Making use of a biological analogy, fermions are as different from bosons as birds are from mammals. The key difference between these two classes of particles is their quantum-mechanical property of spin, which can be understood as angular momentum of their intrinsic rotation. Since bosons feature integer spins, whereas fermions have half-integer spins, the two kinds of particles cannot be turned into one another.

But what if, instead of trying to alter the spin of photons, the properties of their host medium could be modified so as to force them to behave like electrons anyway? Once more drawing on an illustrative analogy, Professor Szameit likens the task to making a sled fit to ride on an asphalt road: A thin film of soapy water would allow it to coast as if on snow. But how to change the road conditions for photons?

Professor Holger Fehske's group at Universität Greifswald researches the abstract behavior of complex quantum systems. Their idea to encode the quantum-mechanical spin property into the host medium fascinates the experimentalists in Rostock: "In principle, it's easy. All you need is a material in which the distances between atoms abruptly change at well-defined points in time," Szameit quips. "Of course, such a thing does not exist." His doctoral student Lukas Maczewsky solved this problem by translating the desired temporal changes of the material into a spatial structure which photons can traverse at light speed. "Precisely at the moment in which the atomic configuration would have to change, we forced light around a tight corner and brought it into close proximity to a neighboring waveguide. Here, the desired interaction is enabled for a very short time," Maczewsky explains his approach.

But how should these waveguides be arranged? The quantum physicist and skillful experimentalist Maczewsky homed in on the solution step by step. He optimized the lattice geometry by programming the laser inscription stage in which the waveguides are engraved in a process similar to CNC milling. After two years of intense research and countless hours in the labs of the Institute of Physics at Universität Rostock, his efforts came to fruition. Two complex, interwoven lattices of intricately curved waveguides guide light exactly as if it was made up of electrons, not photons.

The novel synthetic material allows light to flow along the edges in either direction and without any scattering or reflections. To this end, the crucial property of a half-integer spin that determines the direction of propagation of a wave packet is encoded in the structure of the lattice. "The simultaneous existence of a pair of such counter-propagating edge states is a breakthrough in our field," explains Szameit. The direction taken by the light is solely determined by the initial conditions. The phenomenon first reported by the team of physicists is similar to a perfect diode that is perfectly conductive in one direction, yet exhibits an infinite impedance in the opposite direction – and the two directions can be interchanged at will.

The successful collaboration between the theorists at Universität Greifswald and the experimentalists at Universität Rostock has substantially advanced fundamental science in the field of quantum optics and in particular the research into photonic topological insulators. Until these pieces can be assembled into an optical quantum computer – the holy grail pursued by groups all around the world – numerous challenges remain to be solved. Nevertheless, the physicists' seemingly abstract discovery holds great promise for innovative applications. Optical synapses are one of the ideas Szameit and Maczewsky are setting their sights on. Given the rapid pace of progress, this dream could soon become reality.

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Attachment The curved waveguides of the interwoven sublattices enable light to interact at precisely determined points in time. http://idw-online.de/en/attachment79550

Professor Alexander Szameit and Lukas Maczewsky worked from home during the publication process to observe social distancing in response to the Covid-19 pandemic.
Fotos: K. Szameit und S. Hingst

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