High-dimensional entanglement in an integrated optical platform

Dr Michał Karpiński

Quantum Photonics Laboratory, Faculty of Physics, University of Warsaw

Quantum entanglement is one of the most profound and puzzling consequences of quantum mechanics. At the same time, it is the basis of most applications of quantum mechanics currently being developed within quantum technologies. For example, a quantum computer works by generating and processing entanglement between quantum bits (qubits).

Despite the 2022 Nobel Prize for experimental research on quantum entanglement, our understanding of the entanglement of even the simplest single quantum objects – photons – is not complete. Entanglement between a pair of photons manifests itself through correlations between the results of measurements of physical quantities related to these photons.

For objects to be entangled, they must show close correlations between two quantities, which, according to the uncertainty principle, cannot be precisely determined simultaneously. In the case of electrons, such pairs of quantities are position and momentum. The Heisenberg uncertainty principle states that when we know the exact positions of the particles, their momentums (i. e. velocities – for particles of fixed mass) cannot be known exactly. However, in the case of entangled particles, we have complete correlations: when we measure the position of particle A, we can accurately predict the position of particle B. When we measure the momentum of particle A, we can accurately predict the position of particle B, no matter how far apart they are particles. This is why Einstein described quantum entanglement as “spooky action at a distance” and proposed the hidden classical correlations previously encoded in particles that would explain the observed correlations. However, the research of the 2022 Nobel Laureates (based on earlier work by John S. Bell) proved that entanglement cannot be explained on the basis of classical physics.

Photons can be entangled in polarization (showing correlations for both linear and circular polarizations simultaneously), in position and momentum (i. e. the transverse component of the wave vector) and in time and frequency (i. e. energy, according to the formula expressing the photon energy as the product of the Planck constant and frequency). The latter type of entanglement is poorly studied, although it is very promising in practical terms. The problem with studying time-frequency entanglement stems from the difficulty of making photon arrival time and photon frequency measurements with sufficient resolution. Even when we use single photon detectors with the best time resolution, the photon frequency resolution required to verify entanglement is about 100 times too small. Within this project, we will develop methods to stretch photons in time or frequency by more than 100 times, so as to enable the measurement and modification of pairs of photons entangled in time and frequency.

For this purpose, we will send photons through a material whose index of refraction will change very quickly in time. To obtain sufficiently rapid changes in the refractive index, we will use the latest integrated photonic devices, using an unusual material – lithium niobate. As part of the project, we will develop elements that generate entangled pairs of photons and enable the measurement and use of this entanglement. We will explore the use of pairs of photons entangled in time and frequency to improve measurement sensitivity and secure information transfer. We will also explore the possibilities of using entanglement in time and frequency to speed up quantum computing.