Quantum computing with light

A switch that lets one photon alter the quantum state of another could point the way to both practical quantum computers and a quantum Internet.

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Photo - Graphic: Christine Daniloff

Quantum computers are largely theoretical devices that would exploit the weird properties of matter at extremely small scales to perform calculations, in some cases much more rapidly than conventional computers can. To date, the most promising approach to building quantum computers has been to use ions trapped in electric fields. Using photons — particles of light — instead would have many advantages, but it's notoriously difficult to get photons to interact: Two photons that collide in a vacuum simply pass through each other.

In the Sept. 2 issue of the journal *Science*, researchers at MIT and Harvard University describe an experiment that allows a single photon to control the quantum state of another photon. The result could have wide-ranging consequences for quantum computing and quantum communication, the quantum analog to conventional telecommunications.

A quantum particle has the odd property that it can be in "superposition," meaning it's in two different states at the same time: Fire a single photon at a barrier with two slits in it, for instance, and it will, in some sense, pass through both of them. Where the bits in an ordinary computer can represent either zero or one, a bit made from a quantum particle — a qubit — could thus represent both zero and one at the same time.

For this reason, a string of only 16 qubits could represent 64,000 different numbers simultaneously. It's because a quantum computer could, in principle, evaluate possible solutions to the same problem in parallel that quantum computing promises major increases in computational speed.

But one of the difficulties in building quantum computers is that superpositions of states can be very fragile: Any interaction with its environment can cause a subatomic particle to snap into just one of its possible states. Photons are much more resistant to outside influences than subatomic particles, but that also makes them harder to control; over the course of a computation, a quantum computer needs to repeatedly alter the states of qubits.

The MIT and Harvard researchers' new paper points toward a quantum computer that offers the best of both worlds: stability and control. Moreover, photons in superposition could carry information stored as qubits rather than as ordinary bits, opening the possibility of a quantum Internet.

Slowing light

Vladan Vuletic, the Lester Wolfe Professor of Physics at MIT; his student, Haruka Tanji-Suzuki, a member of the MIT-Harvard Center for Ultracold Atoms (CUA); Wenlan Chen, an MIT graduate student, and Renate Landig, a visiting student, both at CUA; and Jonathan Simon, a postdoc at Harvard, developed an optical switch that consists of a small cluster of cesium atoms suspended between two tiny mirrors in a vacuum cavity. "The only way to make two photons interact with one another is to use atoms as a mediator," Vuletic says. "The [first] photon changes the state of the atom, and therefore it modifies the atom's interaction with the other photon."

When a photon enters the cavity, it begins bouncing back and forth between the mirrors, delaying its emission on the other side. If another photon has already struck the cesium atoms, then each pass through them delays this second photon even more. The delay induced by a single pass through the atoms would be imperceptible, but the mirror-lined cavity, Vuletic explains, "allows us to pass the photon many, many times through the atoms. In our case, it's like passing the photon 40,000 times through the atoms."

When it emerges from the cavity, the second photon thus has two possible states — delayed or extra-delayed — depending on whether another photon has preceded it. With these two states, it could, in principle, represent a bit of information. And if the first photon was in some weird quantum state, where it can't be said to have struck the atoms or not, the second photon will be both extra-delayed and not extra-delayed at the same time. The cavity would thus serve as a quantum switch, the fundamental building block of a quantum computer.

Counting photons

Currently, the extra delay is not quite long enough that delayed and extra-delayed photons can be entirely distinguished, but if the researchers can increase its duration, the switch could have other uses as well. Many potential applications of quantum optics, such as quantum cryptography, quantum communication and quantum-enhanced imaging, require photons that are emitted in definite numbers — usually one or two. But the most practical method of emitting small numbers of photons — a very weak laser — can promise only an average of one photon at a time: There might sometimes be two, or three, or none. The CUA researchers' switch could be tailored to separate photons into groups of one, two or three and route them onto different paths.

Because the switch allows the state of one photon to determine that of another, it could also serve as an amplifier in a quantum Internet, increasing the strength of an optical signal without knocking the individual photons out of superposition. By the same token, it could serve as a probe that detects photons without knocking them out of superposition, improving the efficiency of quantum computation.

"This is one of those really off-scale, super experiments that happens every now and then in science," says quantum-optics pioneer Stephen Harris, a professor of applied physics and electrical engineering at Stanford University. In 1993, one of Harris' graduate students wrote a theoretical paper predicting the effect that the CUA researchers have now demonstrated. "When one does a theory paper," Harris says, "it looks right and so forth, but on the other hand, nobody quite buys it until somebody does an experiment. And this is a magnificent experiment."

Harris acknowledges that the delay that the CUA researchers have introduced is "enough to see, but not enough to be useful." But, he says, the length of the delay is a function of something called "optical depth." "There's little doubt that people will get the optical depth up by a factor of 10," Harris says, "and then this delay will be in the technologically useful range."