In June, Chinese researchers announced a remarkable feat. With the help of an engineered crystal aboard a satellite orbiting Earth, they had beamed a pair of quantum entangled photons from the satellite to receiving stations on two Tibetan mountaintops—located 1,200 km apart—and successfully measured the photons’ quantum properties. This 1,200-km separation was more than ten times the previous record, and it marked a major advance in the quest to use the quantum properties of photons to encode information. This field, quantum communications, holds the promise of sending information under unbreakable encryption.

Quantum communication relies on the quantum entanglement of photons, in which the photons’ spins or polarizations complement each other and stay correlated even if the photons are separated. The idea that entangled photons could be used to encode data has been around since the 1960s, when researchers came up with the idea of using the laws of nature to make banknotes that could not be counterfeited. By 1984, scientists had proven that quantum communication could send invincibly encrypted information. The idea is called quantum key distribution (QKD).

The key property of the crystal is that it is periodically poled, meaning it’s made of alternating, regularly spaced layers whose crystalline domains are oriented in different directions. Most photons pass through unaffected, but a certain percentage get split into pairs of lower energy photons—one with horizontal and one with vertical polarization. The technique is called parametric downconversion. The spacing of the layers in the crystal determines the wavelength of the resulting entangled photons.

Micius generated entangled photons by firing an ultraviolet laser at a specified wavelength through a potassium titanyl phosphate crystal (KTiOPO₄ also called KTP). The key property of the crystal is that it is periodically poled, meaning it’s made of alternating, regularly spaced layers whose crystalline domains are oriented in different directions. Most photons pass through unaffected, but a certain percentage get split into pairs of lower energy photons—one with horizontal and one with vertical polarization. The technique is called parametric downconversion. The spacing of the layers in the crystal determines the wavelength of the resulting entangled photons.

Jian-Wei Pan, a physicist at the University of Science and Technology of China, says this type of crystal was well-suited to the satellite design because it can efficiently generate high-intensity entangled photons with a low-power laser suitable to use in space. Despite that, they detected only about one entangled pair out of six million because of photons lost.
during their passage through the atmosphere. That’s not a practical rate for quantum communications.

That detection is still an impressive feat of engineering, says Alexander Ling, a physicist at the National University of Singapore’s Centre for Quantum Technology. He’s also working on space-based QKD, placing his experiments on high-altitude balloons and small satellites called CubeSats. Like Pan, his team uses commercially available crystals such as $\beta$-barium borate (BBO) to downconvert a photon into an entangled pair. BBO is very resistant to space radiation, he says, whereas KTP requires careful temperature stabilization, rendering the emission system more complex. Other teams have studied periodically poled lithium niobate and lead tetraborate.

Even though many materials are available, Ling says, what are needed are materials that generate more photon pairs with each laser pulse. The more pairs that are created, the higher the communications rate, even with the inevitable losses of photons that result during transmission and detection.

Even better, increasing the number of photons entangled with each other would increase the potential of quantum communications, Ling says. “We could do more interesting things if we could have materials that allow, say, a double pair of photons to be generated more efficiently.” Having four photons entangled together instead of just two would quadruple the amount of information that could be encoded in the system. Researchers have generated up to 12 entangled photons, but the frequency of these events is far too rare for practical applications. One way to increase the number of clusters of entangled photons would be to design photonic crystals with crystalline structures approximately the same size as the wavelengths of light they’re designed to control. “At the moment to get anything more than two photons at a time is very complicated”, Ling says.

### ONE PHOTON AT A TIME

Satellite tests are so far designed as proof-of-concept experiments, and most use existing materials, but meanwhile researchers are trying to develop new, more efficient sources for photons. Many are focusing on single-photon emitters, which produce a stream of identical photons that can be entangled by splitting the beam with an interferometer. “Single photon” means that there is one photon per laser pulse, which can be individually manipulated, whereas ordinary lasers produce hundreds or thousands at once.

One contender for a single-photon emitter is a diamond containing a defect known as a color center because it produces a glint of color when light passes through. In the diamond’s crystalline structure, one carbon atom is replaced with a nitrogen atom, and a neighboring carbon atom is missing, producing the color center. The crystal becomes negatively charged at the site of the defect and changes the wavelength of light entering the crystal.

The trouble with diamond, though, is that it’s hard to get that light out, says Marko Loncar, a professor of electrical engineering at Harvard University’s Center for Nanoscale Systems. First of all, only about 5% of the generated photons are sufficiently uniform to be entangled. Of those, only 5% escape the diamond; the rest get reflected back thanks to the crystal’s high refractive index. Loncar is trying to engineer diamonds’ structure on a nanometer scale using techniques from the microelectronics industry, such as lithography and reactive etching, to create an optical cavity that gives his team more control over the light. “That actually has been a big challenge, because diamond’s a pretty tough material to work with”, he says. On the other hand, if he can make it work, the approach could be easily scaled up to produce many photons from a small device, placing perhaps 100 synthetic diamonds on a 1 cm$^2$ chip.

Other types of diamond defects could work, including one that substitutes a silicon atom for two carbons. “There are hundreds and hundreds of defects in diamonds that one can go through and hopefully engineer something that has good properties”, Loncar says.

Another approach is to put color centers into other types of materials. Silicon carbide is drawing a lot of attention, Loncar says. A semiconductor such as gallium nitride might also work. “Diamond at the moment is probably the best and most promising solid-state platform”, Loncar says, though he admits he’s biased because that’s the material he works on.

Quantum dots, small clusters of semiconductor material that emit different wavelengths of light depending on their size and composition, offer another route to single photons. Pan, for instance, created a single-photon emitter using a quantum dot made of indium arsenide and gallium arsenide embedded in a thin cavity of gallium arsenide. It generates approximately 25 million individual, identically polarized photons per second. The only trouble is, it operates at cryogenic temperatures—even colder than space—making it impractical for a space-borne system, Pan says.

Unlike arsenide versions, nitride-based quantum dots operate at room temperature. They have not yet, however, been made to work well, according to Igor Aharonovich, a physicist at the University of Technology Sydney. Similarly, quantum dots made from perovskites show quantum emission and work at room temperature, but
their performance is inconsistent, and their rate of photon emission is low.

**BRINGING THINGS DOWN TO EARTH**

One of the reasons satellites are a good starting point for QKD is that photons traveling through the vacuum of space are unlikely to hit an atom that will absorb them or alter their quantum properties. Traveling through air or through optical fiber, though, is another story. In these environments, the number of photons that make it to their destination drops significantly. Still, researchers would like to transmit photons on Earth, too. To send their photons through optical fibers, they’d need to use the wavelengths of light—1,330 and 1,550 nm—that other optical communications now use to transmit data and phone calls, so the challenge is to tune emitters to operate at those wavelengths.

For that, the solution may be **adding defects to carbon nanotubes**. “They can act as single-photon emitters at telecom wavelengths at room temperature, and no other material can do that”, says Stephen K. Doorn, a physical chemist at Los Alamos National Laboratory’s Center for Integrated Nanotechnologies.

Carbon nanotubes of the right size emit light at between 1,000 and 1,200 nm. Adding a benzene ring to the wall of the nanotube creates a covalently bonded defect that pushes the wavelength further into the infrared. “We can tune the emission to be deeper into this telecommunication wavelength”, says Han Htoon, a physicist at Los Alamos who works with Doorn. The right chemical functionalization allows them to control the number of defect sites they create, either limiting them to one per nanotube or making sure they’re far enough apart to see where the photons are coming from.

All these technologies need further development to the point where they’ll make quantum communications practical.

Doorn says there is a long way to go in understanding and controlling the chemistry of the nanotubes. Loncar hopes he and other researchers can demonstrate systems that use diamond defects within about five years. And Ling says a quantum future is coming soon. “We think from a technology perspective it’s only a few years out”, he says.

*Neil Savage is a freelance contributor to Chemical & Engineering News, the weekly newsmagazine of the American Chemical Society.*