QUANTUM COMPUTING

Qubits without qubits

Light-based platforms for quantum computing do not require physical qubits

By **Olivier Pfister**

The realization of a quantum computer of practical use is fraught with challenges, including achieving performance that is fault tolerant (has robust error correction) and having a scalable architecture. Many physical platforms are competing to fit the bill, which makes for a vibrant field: quantum information (or qubit) processing by superconducting electronic circuits, by trapped ion or trapped atom systems, or by light fields. For the latter, quantum information is encoded in the amplitudes of light fields (qumodes), which can take a continuous range of values rather than just two distinct values as in qubits. Although qumode-based platforms for quantum information processing allow outstanding scalability compared with that of qubit platforms, they also make error correction much less intuitive than over qubits. On page 289 of this issue, Konno *et al.* (*1*) report the generation of a qubit state encoded in a qumode, providing an important step toward quantum computation with light.

Information handling by a classical computer follows binary rules over bits of information, which are either a 0 or 1. Qubits, on the other hand, can be both a 0 and 1 at the same time, which is called superposition, and superposition also extends to multiqubit states, which can lead to entanglement. Harnessing entanglement seems to be the key to unlocking the power of quantum computing. However, qubits are also eager to entangle with their intractably vast physical surroundings, and this leads to the washout of any quantum computation into a thermal bath. To prevent this, robust quantum error correction is required.

In 2001, Gottesman, Kitaev, and Preskill (GKP) posited that logical qubits could be encoded in physical qumodes—in particular, of light (*2*). Nine years later, it was proposed that an optical GKP state might be experimentally realized (*3*). Such qubit-encoding of information in qumodes (also known as bosonic codes) combines the two worlds of continuous and discrete variables, which have remained decidedly separated in classical information applications, largely because of the inability to correct for small drifts of continuous variables. Although this spelled the limits (and thus demise) of classical analog computing, the quantum situation is very different. GKP-based codes encode and error-correct qubits and, at the same time, correct against small drifts of boson (light) field amplitudes (typically, the position and momentum of a quantum harmonic oscillator). This has led to widespread interest in developing quantum computing platforms that feature bosonic fields alongside qubits.

There are two salient examples of quantum computing platforms that feature boson fields in addition to qubits. One involves the phonon field (mechanical quantum oscillator) that embodies the vibration of a trapped-ion qubit (*4*). The other platform is based on the microwave cavity field coupled to a superconducting qubit (of the transmon kind) (*5*). In both cases, GKP state generation in either a phonon or microwave photon field was enabled by a controlled gate that entangles the field to the qubit.

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There is yet another way to generate bosonic qubit encodings that does not require a physical qubit and is therefore perfectly suited to "pure field" implementations of quantum information such as the quantum optics of propagating light fields. In such implementations, the physical qubits are replaced with physical qumodes—that is, the physical modes of the light defined by frequency, polarization, spatial profile, and propagation direction. In the majority of cases, physical qumodes are defined with exquisite precision by the resonant modes of an optical resonator that also contains a stimulated two-photon emitter. The whole assembly is called an optical parametric oscillator, as opposed to a laser that is based on single-photon stimulated emission. It has been shown theoretically (*6*) and experimentally (*7*–*11*) that one or two optical parametric oscillators can generate all the entanglement needed for quantum computing tasks. There are several reasons for this (*12*). Such oscillators emit a multitude of qumodes, either in the frequency or the temporal domain (or both). This forms the foundation for massively scalable quantum architectures. In addition, qumode entanglement can be engineered to take the form of cluster states that enable measurement-based quantum computing. And there exists a fault-tolerant threshold for qumode-based, measurement-based quantum computing if all qumodes are encoded as GKP qubits (*13*).

Konno *et al.* describe the first experimental generation of GKP states directly over optical qumodes. To achieve this, the authors achieved the comb structure of the GKP wave functions by leveraging the interference in qumode phase space that is present in exotic quantum states of light called "cat" states. In reference to Schrödinger's famous feline caught in a quantum superposition of "alive" and "dead," optical cat states can be viewed as a regular laser beam being both in and out of phase with itself at the same time. By classical physics, one could only understand this as destructive interference (no light present at all). Quantum mechanical light, however, can be placed in such a state and have nonzero intensity. Konno *et al.* generated cat states experimentally by subtracting photons one at a time from the light emitted by an optical parametric oscillator (*14*). They then created the interference of two beams of light in cat states with controlled relative phases and measured one interfering beam. This placed the other beam in a GKP state, which was precisely and unambiguously characterized by use of quantum state tomography.

Although Konno *et al.*'s experiment broke new ground, their GKP state does not yet have the quality required to reach fault tolerance. But there is no fundamental reason that stands in the way of experimental progress beyond this promising start toward a fully fledged photonic quantum computer. ■

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