Editorial

Perspective on hybrid quantum information processing: a method for large-scale quantum information processing

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1. Introduction

There are two encoding schemes for quantum information processing (QIP). One is called qubit encoding which corresponds to ‘digital’ encoding, precisely speaking, quantum information is encoded as a superposition of two orthogonal states. The other is called continuous-variable (CV) encoding which corresponds to ‘analog’ encoding, precisely speaking, quantum information is encoded in a wave function with a continuous basis or in amplitude and phase of wave. In some sense, qubit encoding corresponds to a particle picture of quantum mechanics and the CV one corresponds to a wave picture. Both have advantages and disadvantages and grew separately. Here, qubit encoding is widely used, because it has a high-fidelity nature like a digital TV.

There are two models of QIP for both encoding schemes. One is the quantum circuit model, where a quantum circuit consists of quantum gates which process input quantum states \[1, 2\]. The other is the measurement-based model or one-way QIP, where a large-scale entangled state called a cluster state is initially prepared and then we make a measurement and feedforward depending on the desired operations \[3, 4\].

In the case of optical realization of QIP, there are big problems for the quantum circuit model. We need a large-scale quantum circuit for large-scale QIP. It is because an optical qubit is a ‘flying qubit’ and we need a real quantum circuit for the processing, which is in sharp contrast to a ‘stationary qubit’ like an ion and an atom and they do not need a real quantum circuit for QIP. Also, we have to change the quantum circuit when we make a different QIP. Again, it is because we need a real quantum circuit to process ‘flying qubits’, while the other ‘stationary qubits’ do not need real quantum circuits and we just change the control sequence.

2. Time-domain multiplexing

The problems of optical QIP with the quantum circuit model can be solved with our newly developed time-domain multiplexing method for one-way QIP, where one optical beam is regarded as a train of wave-packets or temporal modes \[5–7\]. We recently succeeded in deterministic creation of a CV one-million-temporal-mode linear cluster state with this method \[7\]. The big advantage of this method is that we can continue QIP forever. There is no time limit. It is because we make a measurement within the fundamental laser coherence time. Furthermore, this
methodology can be extended to two-dimensional (2D) [5, 8]. We can deterministically create a 2D CV cluster state with the size of $10^6 \times \infty$ only with four squeezed light beams, five beam splitters, and two delay lines [8]. So we can make a large-scale universal one-way QIP with the 2D CV cluster states in principle.

3. Hybrid QIP

CV QIP has a disadvantage. That is the inherent low fidelity of operation of CV QIP, because perfect fidelity of the operation needs an infinite amount of energy. This is why we have to make a hybrid QIP [9, 10]. Here, the hybrid QIP means that qubit encoding with CV methodology and CV processing with the time-domain multiplexed CV cluster states. In some sense, we use full quantum mechanics—particle and wave pictures—here. The reason why we need qubit encoding is that it has an inherent high-fidelity nature and we know a lot of schemes of quantum error correction by using qubit encoding. One of the examples is the Gottesman–Kitaev–Preskill (GKP) scheme [11], where qubits are encoded with CV methodology, i.e., quantum information is encoded as the amplitude and phase of an optical wave. Menicucci pointed out that we can make a fault-tolerant one-way QIP by using the GKP scheme and CV cluster states created with 20.5 dB of squeezing [12], where squeezed light is a resource of the entanglement. Here, the world record of squeezing is 15 dB at the moment [13] and it can be extended to 20.5 dB in principle. For this purpose, we can enjoy the big advantage of time-domain multiplexing. As mentioned above, we only need four squeezed light beams, five beam splitters and two delay lines for the creation of ultra-large-scale 2D CV cluster states [8]. Since degradation of squeezed light occurs due to optical losses, it is very important that we need very small numbers of optics for the creation.

Hybrid QIP has another advantage. We can handle many photons and wave-packets (temporal modes) simultaneously. This means that we can have redundancy of quantum information for quantum error correction. For example, we can make a quantum error detection code for an amplitude-damping (photon-loss) channel or a dual-rail qubit with a single photon and two wave-packets like $C_0[0, 1] + C[1, 0]$. We already succeeded in the teleportation [14], where one-way QIP can be regarded as sequential teleportation. Similarly, we can make quantum error correction codes with four photons and two wave-packets like $C_0[0, 4] + [4, 0]/\sqrt{2} + C[2, 2]$ (Bosonic code) [15] and with four photons and four wave-packets like $C_0[(0, 2) + [2, 0)] \otimes (0, 2] + [2, 0)]/2 + C[1, 1, 1, 1]$ (NOON code) [16]. We recently succeeded in teleportation of the primitive, $C_0[(0, 2) + [2, 0)]/\sqrt{2} + C[1, 1]$ [17]. This methodology can be extended to quantum error correction codes with many photons and wave-packets which are more fault-tolerant. By using this advantage of hybrid QIP, we will try to find the scheme which enables us to realize fault-tolerant hybrid one-way QIP with CV cluster states created even with 10 dB of squeezing. Here, 10 dB of squeezing can be achieved by using ordinary technologies.

4. Outlook

We already have a methodology to make a large-scale hybrid QIP. The final problem should be to find a way to realize fault-tolerance. Moreover, we know a methodology [18] to realize all-optical CV and hybrid one-way QIP, which is inherently very fast, because the carrier frequency is optical frequency—100 THz. If we can realize it, the clock frequency of our quantum computer can be on the order of THz, which is three-orders faster compared to conventional computers.
This means that we can enjoy speed-up of computation even without a special quantum algorithm like Shor’s algorithm [19].

References

[1] Feynman R P 1985 Opt. News 11 11
[2] Lloyd S and Braunstein S L 1999 Phys. Rev. Lett. 82 1784
[3] Raussendorf R and Briegel H J 2001 Phys. Rev. Lett. 86 5188
[4] Menicucci N C, van Loock P, Gu M, Weedbrook C, Ralph T C and Nielsen M A 2006 Phys. Rev. Lett. 97 110501
[5] Menicucci N C 2011 Phys. Rev. A 83 062314
[6] Yokoyama S, Ukai R, Armstrong S C, Somphiphathphong C, Kaji T, Suzuki S, Yoshikawa J, Yonezawa H, Menicucci N C and Furusawa A 2013 Nat. Photon. 7 982
[7] Yoshikawa J, Yokoyama S, Kaji T, Somphiphathphong C, Shiozawa Y, Makino K and Furusawa A 2016 APL Photonics 1 060801
[8] Ukai R 2014 Springer theses Multi-Step Multi-Input One-Way Quantum Information Processing with Spatial and Temporal Modes of Light (Tokyo: Springer)
[9] Furusawa A and van Loock P 2011 Quantum Teleportation and Entanglement-A Hybrid Approach to Optical Quantum Information Processing (Weinheim: Wiley-VCH)
[10] Andersen U L, Neergaard-Nielsen J S, van Loock P and Furusawa A 2015 Nat. Phys. 11 713
[11] Gottesman D, Kitaev A and Preskill J 2001 Phys. Rev. A 64 012310
[12] Menicucci N C 2014 Phys. Rev. Lett. 112 120504
[13] Vahlbruch H, Mehmet M, Danzmann K and Schnabel R 2016 Phys. Rev. Lett. 117 110801
[14] Takeda S, Mizuta T, Fuwa M, van Loock P and Furusawa A 2013 Nature 500 315
[15] Chua I L, Leung D W and Yamamoto Y 1997 Phys. Rev. A 56 1114
[16] Bergmann M and van Loock P 2016 Phys. Rev. A 94 012311
[17] Okada M, Takase K, Fuwa M, Takeda S, Yoshikawa J, van Loock P and Furusawa A 2017 Conference on Lasers and Electro-Optics - European Quantum Electronics Conference (Munich)
[18] Ralph T C 1999 Opt. Lett. 24 348
[19] Shor P W 1994 Proc. 35th Annual Symp. on Foundations of Computer Science pp 124–34