Initiatives for New Computers using Quantum Technology

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Advances in current digital computer technology are appearing to approach saturation, and there is much active R&D on computers that use physical systems to solve problems more efficiently than existing computers. Quantum computers are attracting attention in this research, as a technology that can dramatically increase efficiency in terms of computing time and energy consumed relative to conventional computers by using quantum superposition states. Recently, large enterprises such as IBM, Google, and Microsoft are putting great effort into developing quantum computers. This article introduces initiatives at NTT to implement new computing devices using physical systems. Section 1 discusses a new type of computer called a Coherent Ising Machine (CIM), which uses quantum electronics technology developed at NTT. Section 2 introduces experiments demonstrating quantum mechanical principles using qubits, which are the basic device used in the quantum computer.

1. New theoretical computer using light: the “Coherent Ising Machine”

NTT is conducting R&D on a computer called a Coherent Ising Machine (CIM), based on new principles. A CIM uses quantum electronics technology and is able to solve combinatorial optimization problems efficiently. It uses a type of oscillator called a degenerate optical parametric oscillator (DOPO), which is able to solve Ising model energy-minimization problems rapidly. The Ising model is a theoretical model of a set of interacting atomic spins.

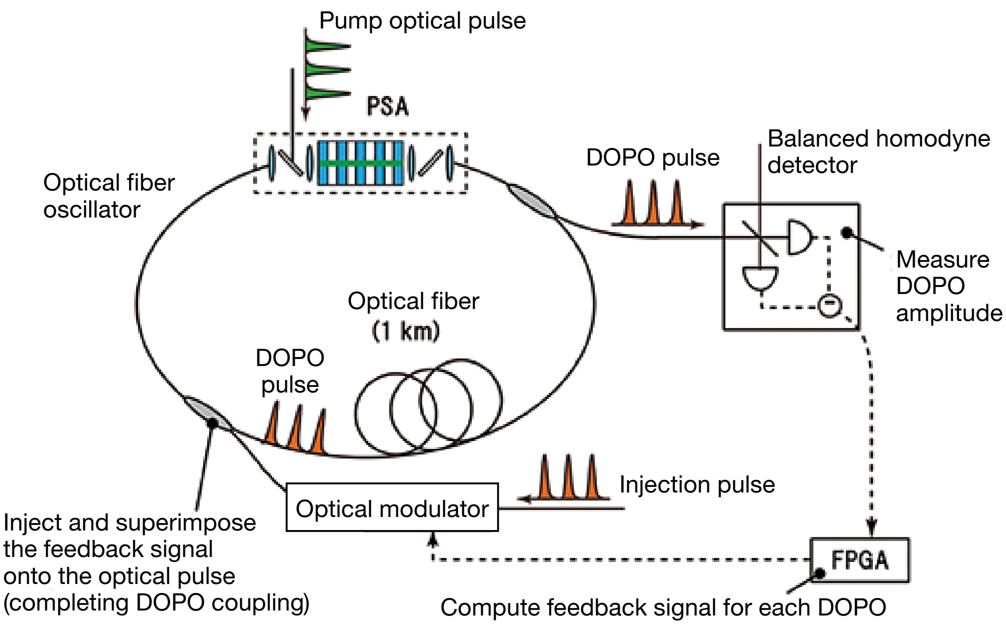
A DOPO is a special type of optical oscillator for which, above the oscillation threshold, the oscillation phase can only take one of two values, 0 or π, relative to the phase of the pump beam/light, which is described below. Thus, by assigning a phase of 0 to up-spin and π to down-spin, the DOPO phase can be a stable expression of the Ising spin state. A DOPO is generated by placing a special type of optical parametric amplifier called a phase-sensitive amplifier (PSA)[1] in the optical oscillator. When a pump wave and a signal wave are injected into a non-linear optical medium, the PSA amplifies the signal wave and also generates an “idler” wave, which has a frequency corresponding to the difference between the signal wave and the pump wave. Here, if the signal and idler waves have the same frequency, the amplifier efficiency is maximized for signals with phase of 0 or π relative to the pump wave. Placing a PSA in the optical oscillator creates an oscillator that only oscillates at phases of 0 or π relative to the pump wave.

A single optical system with N independent DOPO pulses can be generated by using a pulsed-state pump wave with this optical oscillator, and setting the period of the optical oscillator to N-times the interval of the pump wave pulses[2]. NTT has successfully generated sets of 5000 to 1 million time-multiplexed DOPO pulses using optical oscillators of lengths from 1 to 20 km and pump wave pulses with feedback frequencies from 1 to 10 GHz[3-6].

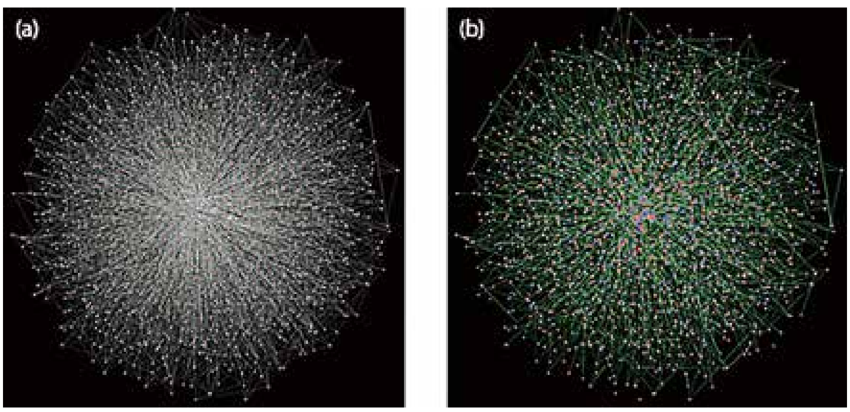
Interaction between DOPO pulses has been reported earlier, using a direct coupling method with a delay-interferometer[2,3], and a measurement-and-feedback (MFB) method[5,6]. Here we discuss a method using MFB. A schematic diagram of a CIM using MFB is shown in Figure 1. A PSA in a 1-km optical fiber oscillator is driven with pump wave pulses repeating at a frequency of 1 GHz, which generates a set of approximately 5000 DOPO pulses. When the pump wave is input to the PSA, a noise wave pulse called a squeezed vacuum wave is generated, which then circles the oscillator, and the pulse is amplified gradually by repeated PSA amplifications. After approximately 1000 cycles, DOPO characteristic phase separation occurs. At this point, a beam splitter is used to extract some of the energy of a 2048 DOPO pulse set in each cycle of the DOPO oscillator, and the amplitudes are measured using a balanced homodyne detector. The result of measuring these amplitudes (a 2048 element vector) is input to a field programmable gate array (FPGA). The spin interactions representing the Ising model problem to be solved (a 2048x2048 matrix) are input to the FPGA ahead of time. By computing this product, the FPGA produces feedback signals for each DOPO pulse, to implement the desired connections. Coupling between DOPO pulses is achieved by using the optical modulator to inject optical pulses with the same frequency as the DOPO pulses into the oscillator, superposing them on the DOPO pulses. Using this method, we were able to realize two-body interactions for all combinations among 2000 spins (approximately 4 million, including directed couplings). The set of vacuum squeezed optical pulses initially has random phases but with repeated MFB interactions, the entire system quickly settles to a combination of phases that is optimally stable. The solution to the input Ising problem is obtained by reading out the phases of each DOPO pulse after oscillation.

With collaboration from NII, Osaka University, and Tokyo University, NTT has built an MFB-based CIM and used it to search for solutions to large-scale combinatorial optimization problems (Figure 2)[5]. In experiments conducted in 2016, we searched for a solution to a fully-connected graph max-cut problem with 2000 elements and achieved an equivalent solution approximately 50 times faster than a CPU implementation of simulated annealing,. NTT is currently developing CIM equipment that is more compact and has stable operation over longer periods of time under the technology brand name "LASOLV", and is engaging in R&D to apply it in society.

■ Figure 1: CIM configuration (from NTT Technical Journal Vol. 2017.5, pp. 11-14, 2017)



■ Figure 2: Using the CIM to solve a max-cut problem. (a) Visualization of a graph problem with 2000 vertices and 19900 edges. Vertices are shown as pink dots and edges as white lines. (b) Solution found by the CIM. Vertices are partitioned into red and blue groups, and edges shown in green are cut. (from NTT Technical Journal Vol. 2017.5, pp. 11-14, 2017)



2. Demonstration of quantum mechanical principles using a quantum bit

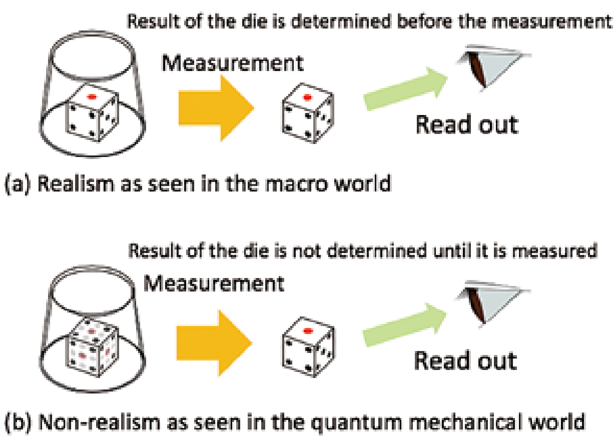
Ion-trap quantum computers and superconducting quantum bits are technologies attracting attention for realizing quantum computers. The former uses the microscopic physical system of a natural atom as a quantum bit, so it is isolated from surrounding noise and has the long coherence times necessary for quantum computations. In contrast, the latter uses circuit elements such as capacitors, inductors and Josephson junctions, so circuits can be designed freely and are very extendable and controllable. However, superconducting quantum bits are created with semiconductor nano-fabrication processes and are macroscopic physical systems (several μm) compared to atoms, so they are susceptible to the effects of noise and have short coherence times. Coherence characteristics have been improved dramatically recently, using circuit design techniques, achieving gate fidelity comparable to ion traps, but a huge amount of effort has been invested in improving coherence characteristics in superconducting quantum bit research in the past 20 years. In this process, NTT has used the fact that superconducting quantum bits are a macroscopic system to investigate the scale to which quantum mechanics can be applied, which has been a fundamental question since quantum mechanics was discovered.

Realism and Non-realism

Consider an experiment in which a die is placed in a cup and shaken. If the cup is opened and the die shows one dot, we assume that the die showed a one, even before the cup was opened. We assume, when we observe an object in a particular state, that it was in that state before the observation and that the observation did not affect the state. This way of thinking is referred to as "realism" and is taken for granted in everyday life (Figure 3(a)).

However, according to quantum mechanics, objects exhibit strange states called "superposition states," which are contrary to everyday common sense. Consider the example of a quantum die in Figure 3(b), conforming to quantum mechanics. A superposition state with the die showing values from 1 to 6 with equal probability exists in the cup, and the moment the cup is opened and observed, one of these states is decided. This property, in which the state is not determined before the observation, and only determined by the fact of the observation, is called "non-realism," and is known to occur in microscopic systems (atoms, electrons, etc.) conforming to quantum mechanics. Of course, it is not possible to verify non-realism using macroscopic objects like dice, but the question of the scale of macroscopic objects to which quantum mechanics can be applied is very interesting.

■ Figure 3: Realism and non-realism



Preparing macroscopic systems

In 1985 Professor Anthony Leggett from Illinois University predicted a superconducting ring with Josephson junctions could realize a state with currents flowing in the ring in both clockwise and counter-clockwise directions, and published a paper showing how to demonstrate that non-realism can occur in macroscopic systems[7]. Later, as interest in quantum computers increased, superconducting circuits were developed, and a superconducting ring with three junctions became established as the superconducting flux quantum bit (Figure 4(a)). When magnetic field through the ring approaches a half-integer multiple (…-0.5, 0.5, 1.5, …) of a flux quantum, Φ_0, the state of the current flowing clockwise (or counter-clockwise) in the flux qubit stabilizes. Worth mentioning is that the size of the flux qubit (several μm) is very large compared to electrons and atoms, and the current (several 100 nA) amounts to a flow of a trillion electrons per second. NTT has verified quantum superposition states in these currents, which are macroscopic physical quantities, and aimed to verify non-realism properties in them.

Verification of non-realism

Prof. Leggett proposed a thought experiment in which the state of current flow in a superconducting ring is measured at several times. It indicated that if measurements could be made without disturbing the state and realism is established, then a correlation between the measured values would verify that the Leggett-Garg inequality is satisfied. That is to say, if it could be shown that this inequality is violated when making measurements that do not disturb state, then non-realism would be demonstrated, and subsequently quantum mechanics would apply to the system. At NTT, we have derived conditions that are mathematically equivalent to this inequality, and used the following method to verify non-realism experimentally[8].

If a flux qubit conforms to quantum mechanics, then a quantum superposition state, $|-1\rangle+|1\rangle$, will be realized when it is exposed to a microwave equivalent to the energy difference between the two-current states, $|-1\rangle$, $|+1\rangle$, for a suitable amount of time. When this microwave irradiation is repeated four times, the state returns to its original state, as shown in Figure 4(b), so this exposure to microwaves is called a state operation ($\theta=\pi/2$). This state operation is used to conduct the two experiments shown in Figure 4(c). A flux qubit with state $|-1\rangle$ is first prepared, and after repeating the state operation twice, and readouts of the final state are compared. The difference is that between the state operations, a measurement is taken or not. If realism is true, then the state before and after the measurement will not change, so no difference will appear between the two tests, and the difference d_p between the read-out expected values $\langle Q_3\rangle$ will be 0.

Next, consider the case where non-realism is shown establishing that quantum mechanics applies. In the second experiment in Figure 4(c), after applying the operation twice, the initial value of |-1> will become |1>, and the expected readout value will be 1. Conversely, in the first experiment, a measurement is taken after the first state operation, on the superposition state |-1> + |1>. With this observation, a probabilistic quantum projection to |-1> or |+1> occurs, so the next operation produces a superposition state of |-1> + |1> or |-1>-|1>. When this is read out, the expected value is 0 in both cases. Thus, the difference in expected values for the two experiments, $|d_\rho|$, is 1. In the actual experiment, there are limitations on the precision of the readout, so $|d_\rho|$ is a finite value less than 1. From the discussion above, we expect that if realism holds true, $d_\rho=0$, and if non-realism holds true, $|d_\rho|>0$. We refer to this as the main experiment.

Note that ideally, our main experiment is conducted using "non-disturbing measurements", but noise and imperfections in measurements results in a small amount of disturbance to the state. To evaluate this quantitatively, we also conducted a control experiment. We prepared pure |-1> or |+1> states with no superposition after the first state operation and then evaluated the difference in readout results with and without a measurement. Here, when preparing $|-1\rangle$ and $|+1\rangle$ states, the expected differences in readout are defined as d_g and d_e respectively. Ideally, $d_g=d_e=0$, but small variations are generated due to disturbance of the state by the measurements. Results of this experiment are shown in Figure 4(d). d_ρ greatly exceeds the values between d_g and d_e, indicating that the behavior of the flux qubit cannot be explained by realism, and that non-realism holds true. The separation of d_ρ from d_g and d_e is approximately 84 times the standard deviation of experimental error, verifying that quantum superposition states were realized in the flux qubit, and that quantum mechanics holds true for this macroscopic system.

3. Conclusion

In the first part of this article, we introduced the CIM, which is a new type of non-Von Neumann computer that surpasses conventional computers in solving particular optimization problems. We intend to increase the scale of this system and use it to solve problems in real society in the future.

In the second part, we showed how quantum superposition states, a basic quantum mechanical property which had only been verified at the microscopic scale of individual electrons and other atomic particles, can also be seen in macroscopic currents flowing in a superconducting ring on a scale that can be observed using an optical microscope. We hope to verify non-realism at even larger scales in the future.

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Figure 4: Test method and results