論 文 の 内 容 の 要 旨

Abstract

論文題目 Title of Dissertation	Quantum Theory and Experimental Demonstration of a Coherent Computing System with Optical Parametric Oscillators （光パラメトリック発振器を用いたコヒーレント計算機の量子論及び実装実験）
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It is quite non-trivial to give the best answers of many tasks in our daily life and business, such as planning an efficient travel route, arranging a good rotating roster and designing a compact electric circuit. Such problems can be modeled as combinatorial optimization problems, and many of them belong to non-deterministic polynomial (NP)-complete and NP-hard classes. It is believed that they cannot be solved in a polynomial time, and are intractable for digital computing algorithms.

One of the fundamental combinatorial optimization problems relevant with physics is to find a ground state of Ising Hamiltonian. This is called Ising problem and includes NP-Hard instances. Many schemes originating from physics such as simulated annealing, quantum annealing and adiabatic quantum computation are being vastly studied for this problem. However, their full potentials are still being explored. We have recently proposed a new emulator for the Ising spin system named coherent Ising machine, which is an oscillator network coupled with mutual injections. In the machine, each spin is mapped to a degree of freedom in the intracavity field of each oscillator, and the spin-spin interaction is mimicked by the mutual injections. The problem Hamiltonian is incorporated in the total photonic gain i.e. the effective loss of the system. The gradually pumped system is expected to oscillate in the state with the

artificial spin configuration giving the minimum loss, which corresponds to one of the ground states.

There are two types of the Ising machine proposed, the injection-locked laser network machine and the degenerate optical parametric oscillator (DOPO) network machine, and the latter has a binary nature. A DOPO has one of the two relative phases 0 or π, and these binary and out-of-phase states can be utilized as an artificial spin. The initial benchmarking with a semi-classical model has shown a promising result on NP-hard instances up to 20 variables. However, regarding its working principle, it is important if the machine has any quantum properties available for computation, because quantum computing is the only paradigm having some theoretical evidences to possibly surpass digital computing. Also, proof-of-principle experiments and prospects for the realization of a system for large-size problems are desired.

In this thesis, I study the machine based on DOPOs both theoretically and experimentally. On the theoretical side, I focus on the physics of the DOPO network coupled with mutual injections and investigate its quantum states. Here, I develop a fully quantum mechanical model for the network using the positive P representation, and numerically simulate the system of two DOPOs with out-of-phase mutual injections. Here, I explicitly consider the signal field in the mutual injection path between the two DOPO facets as a cavity mode. The stochastic simulation with a small noise parameter has been conducted under the gradually increasing pumping rate from the below to above of the threshold. The result has shown that small incoherent intracavity loss rates are indispensable in quantum effects in the system. When the incoherent loss in the injection path has the same order as the coherent transmission rates at the DOPO facets, the signal fields in the two DOPOs have the quantum correlation in terms of the squeezed quadrature amplitude $\hat{p} = (\hat{a} - \hat{a}^\dagger)/2i$. This also indicates the entanglement between the two DOPO fields. When the loss of the injection path is fairly smaller than the transmission, the two intracavity fields can show weak coherent superposition components via the small fringes in the distribution functions for $\hat{p}$. The superposition components with a small noise parameter and under a relatively non-transient operation have not been expected by previous relevant studies on a single DOPO. It suggests that the mutual injection path storing the squeezed vacuum is simple realization of the squeezed reservoir, which suppresses the decoherence on the superposition components.

On the experimental side, I perform the first-time and second-time experimental demonstrations of the coherent Ising machines based on degenerate optical parametric oscillators in collaboration with Alireza Marandi at Stanford

University. The system is based on the time-multiplexed DOPO network composed of femtosecond DOPO pulses running in a single ring cavity. Each DOPO pulse randomly takes one of the binary phase states with their phase difference being π and is utilized as an artificial spin. The signal pulses keep the phase coherence allowing the interference between them. Mutual injections are achieved by the optical delay lines implemented with pairs of input and output couplers placed in the resonator. The first system built by us contains four DOPO pulses at 2 μm and three delay lines. Also, I have designed and constructed another system with 16 signal pulses at telecom wavelengths. They have been applied to instances on one-dimensional ring and cubic graphs. Very high success probabilities to find ground states of them indicate a big potential of this machine for intractable optimization problems.